The University of Chicago

STUDIES IN MINOR FOLDS

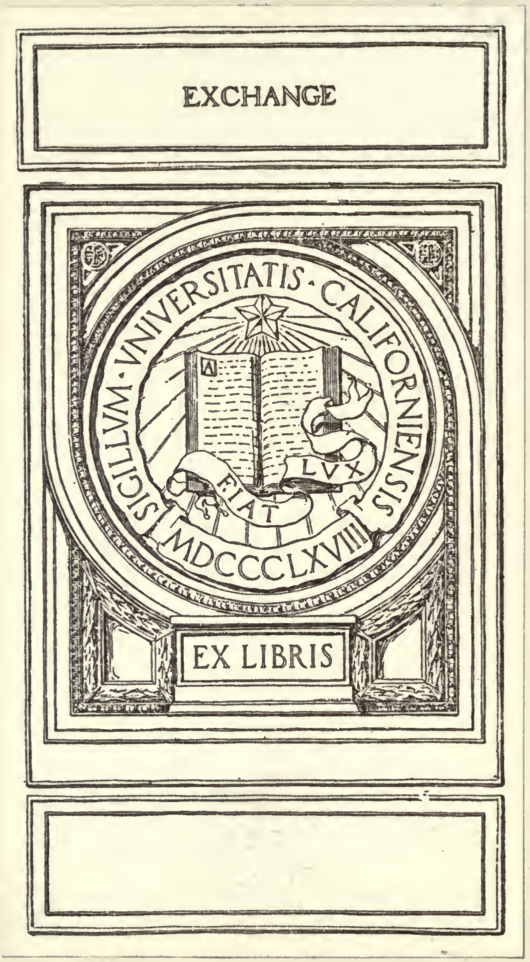
A DISSERTATION

SUBMITTED TO THE FACULTY
OF THE OGDEN GRADUATE SCHOOL OF SCIENCE
IN CANDIDACY FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY

BY
CHARLES ELIJAH DECKER

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS
1920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General Map Showing Location of the Tri-State Lake Strip along the South Shore of Lake Erie and Adjacent Regions.

INTRODUCTION

The data on which these studies are based have been secured from a narrow area south of Lake Erie, extending from Cleveland across northeastern Ohio, northwestern Pennsylvania, and into New York as far as Dunkirk (see Plate I). A few folds on Lake Ontario were studied, both in northern New York and southern Canada. A number of intermediate points between Niagara and Dunkirk were visited, as were several others farther southeast in New York and westward from Cleveland to Sandusky, Ohio. A few folds were studied in the folded areas of the Arbuckle and the Wichita mountains of Oklahoma.

In geological literature much attention has been given to structural studies, especially to folds and folded regions. However, the major folds have seemed so to overshadow the minor ones that the latter have been passed over, being considered relatively unimportant. Economic considerations have directed attention to some minor folds which received no consideration as having any importance from a structural standpoint. Of the folds of this type, some of the most noteworthy are those in Pennsylvania, West Virginia, and Oklahoma for oil and gas, Wisconsin for lead and zinc, Michigan and Wisconsin for iron, and Australia for gold.

It is the purpose in this paper to illustrate by diagrams and photographs a series of types of minor folds; to illustrate and study briefly a few minor folds in their relation to major ones; to illustrate a larger number of small folds in the midst of horizontal or gently dipping strata, showing their characteristics, methods of origin, age, and relation to faults; and finally, to connect these minor deformations, in so far as

possible, with larger movements, and show their significance, as indicating the presence of compressional stresses in the rocks in the interim between the great periods of deformation and mountain-building.

The writer makes grateful acknowledgment for direction and help to Professor R. D. Salisbury, under whose supervision this study has been pursued, to Professor T. C. Chamberlin for helpful suggestions, to Professor R. T. Chamberlin for valuable criticisms and suggestions, to Frank Gahrtz for work on figures and maps, and to W. E. Coon for field assistance.

TYPES OF FOLDS

The most common type of fold is the anticline. Gilbert has defined it as one in which the strata dip in two directions away from the axis.[1] Anticlines are extremely variable in form, so that a number of distinct types have been recognized. These types are symmetrical, unsymmetrical, overturned, recumbent, open, and closed folds, besides the compound form—the anticlinorium.

Symmetrical anticline.—A symmetrical anticline is a fold whose axial plane is vertical and on which the dip at corresponding points on the two limbs is equal. A diagram of a symmetrical fold is shown in Figure 1. In this figure *cd* is a line in the axial plane which divides the anticline into two equal and symmetrical limbs. The fold is represented as having the crest eroded and restored by the dashed lines. Examples of folds of this general type were found near Westfield, New York; North East, Erie, Girard, and Meadville, Pennsylvania; and Andover, Conneaut, Kingsville, and Painesville, Ohio. A fold of this type which, however, is not perfectly symmetrical, is shown in Figure 2. It crosses the bed of Walnut Creek 5 miles south of Erie, Pennsylvania. The dip to the west is 14° and to the east is 17°. The axis trends N.10°W. The beds vary in thickness from 2 to 7 inches, and consist chiefly of blue shale with some sandy beds interspersed. The stream has eroded the crest of the fold, cutting deeply into the axis forming the basin for the pool in the foreground. The loose material on top of the fold is shingle, contributed largely by the tributary which enters at the left of the crest. A more perfectly symmetrical fold is shown in Figure 31, in which the dip is 8° in each limb. Among the other folds of this type mentioned above, some of those near Conneaut and Painesville are more gentle and open, while some near Westfield, Andover, and Meadville are smaller and more closed.

[1] G. K. Gilbert, *Amer. Jour. Sci.*, 3d Ser., XII (1876), 21.

Unsymmetrical anticline.—An unsymmetrical anticline is a fold in which the axial plane is inclined and in which the strata dip more steeply in one limb than in the other. A diagram of a fold of this type is shown in Figure 3. In this figure the line *cd* marks the inclined axial plane which divides the fold into two very unsymmetrical parts. The dip in

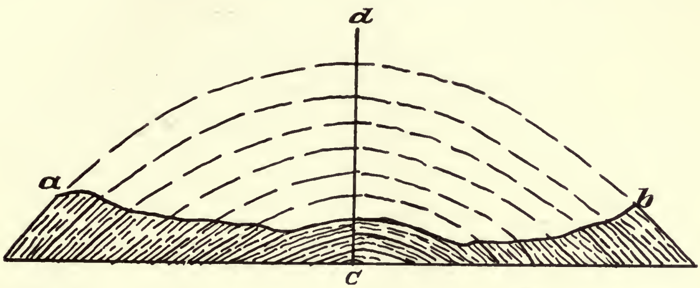


FIG. 1.—Diagram of a symmetrical anticline from which the crest has been eroded. Restoration of the eroded part is shown by dotted lines.

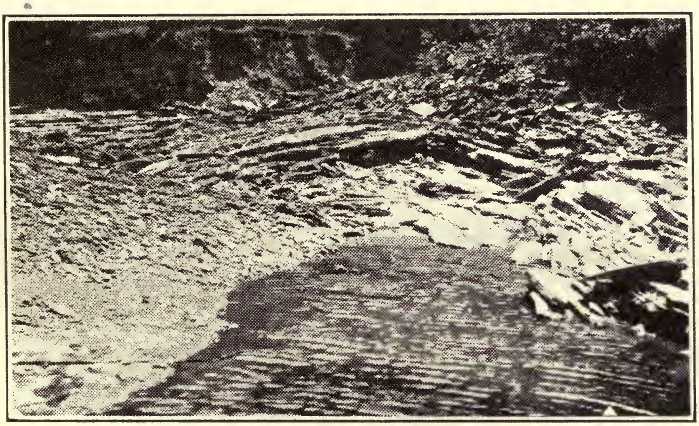


FIG. 2.—Photograph of a symmetrical anticline in the bed of Walnut Creek, 5 miles south of Erie, Pa.

the limb at the right is much greater than in the one at the left. A fold of this type deforms the west bank of the Chagrin River, a mile west of Chagrin Falls, Ohio. Figure 4 is a photograph of this fold. The steep dip downstream to the northeast is 29°, and the gentler dip upstream is 11°. The fold is about 160 feet wide, and deforms the rocks of a terrace 56 feet high. The rocks consist of alternating sandstones

and shales in the Bedford formation.[1] (See Table III.) The heavy sandstone bed, which stands out clearly in the picture, is 17 inches in thickness. This bed has been slightly faulted at the crest of the fold, the horizontal displacement being 2 feet and 10 inches. The distinctness of the brecciated zone above this stratum suggests that the

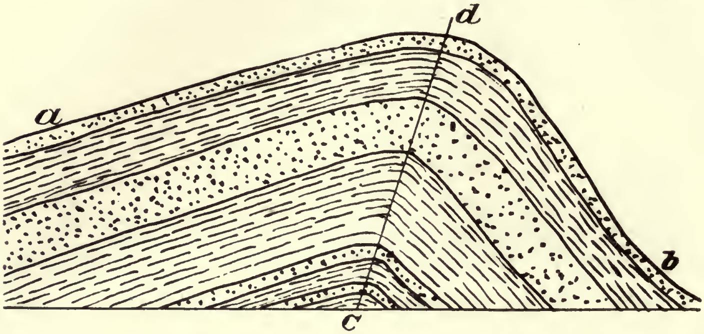


FIG. 3.—Diagram of an unsymmetrical anticline

FIG. 4.—Photograph of an unsymmetrical anticline near Chagrin Falls, Ohio

remaining strata above were affected by this fracture. While the steep side of the bank is weathered and partially covered with vegetation, the fact that a path was started from the top of the terrace along a natural depression in the line of the axis seems to be another indication that the fault affects all of the uppermost strata. Here, then, a fold below

[1] C. H. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912), pp. 197, 198.

passes into a fault above.[1] This same relation of fold and fault was found 25 miles to the northeast along Paine Creek. This anticline is only one of a large number with marked asymmetry that exist in the area. Two distinct examples of this type occur within half a mile of

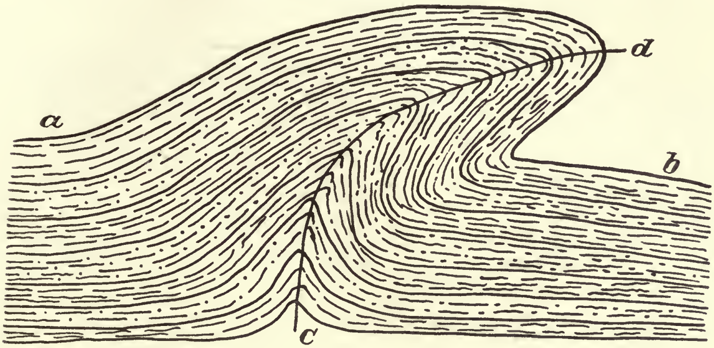


FIG. 5.—Diagram of an overturned fold

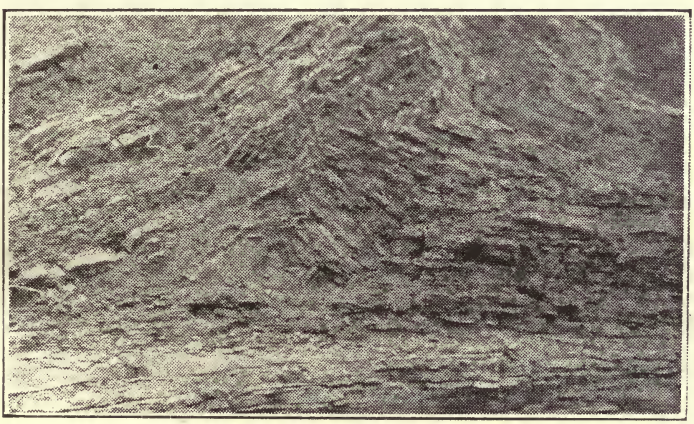


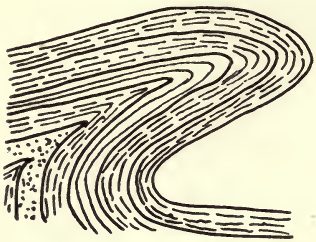
Fig. 6.—An overturned fold on the northwest shore of Lake Ontario near Burlington, Ontario.

each other near Girard, Pennsylvania, and in them the highly inclined limbs are toward one another.

Overturned anticline.—When the stress or resistance differs greatly on the opposite sides of a fold, the strata on one side are raised and the

[1] Chamberlin and Salisbury, *Geology*, I (1905), 516, Fig. 121; and Bailey Willis, *Thirteenth Ann. Rept. U.S.G.S.*, Part II (1893), Plates 79, 93, 94.

top of the fold is thrust forward and bent over until the strata on both sides of the axis dip in the same general direction. By this process the overturned anticline is formed. Figure 5 is a diagram of an overturned fold. The axis is bent to the right to such an extent that the younger beds beneath the axis have their dips reversed toward the left, or in the



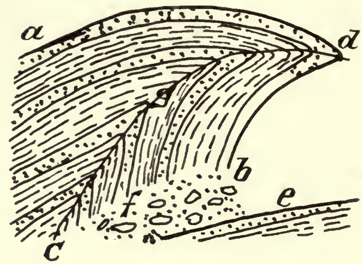


FIG. 7*a*.—Diagram of a recumbent anticline (after Van Hise)
FIG. 7*b*.—Diagram of an overturned fold with recumbent top

FIG. 8.—An overturned fold with recumbent top, near North East, Pa.

same general direction as those above the axis. Figure 6 shows an overturned anticline in the sandy shales on the northwest shore of Lake Ontario, 8 miles northeast of Burlington, Ontario. The fold is in the uppermost shales in a 14-foot terrace, and the strata in the overturn are thrust up into the terrace material in a way to indicate the recency of the fold. This is one of several small folds above the end of a thrust fault whose plane has the low angle of 5° to 14°. Two other

overturned folds were found in northern Ohio, one 3 miles south of Willoughby, along the Chagrin River, and one 6 miles southwest of Conneaut, along Conneaut Creek. On the south side of Lake Ontario, at Thirty Mile Point, there is an anticline with overturned axis. The overturned top of the fold incloses glacial drift beneath it. This fold is shown in Plate 19 in the back of the *Niagara Folio.*

Recumbent fold.—When an anticline is so far overturned that the inverted strata approach a horizontal position,[1] it is called a recumbent fold. A diagram of such a fold is shown in Figure 7*a*. This is taken from Van Hise, who in his article on "North American Pre-Cambrian Geology" gives an excellent discussion of the various types of folds.[2] No fold closely approaching the form of the one in Figure 7*a* was found in the area studied, but Figure 7*b* is a diagram of one one-fourth mile south of North East, Pennsylvania, on the east side of Sixteen Mile Gulf. The notebooks in the photograph of the same fold (Fig. 8), one on the axis and one down in the right foreground, are on the same stratum. By referring to Figure 7*b*, it will be seen that the strata have been broken at the base of the right limb and overthrust to the right. In this figure the bed beneath *e* has its continuation at *fg*. This is the only example of a fold found in this area approaching the recumbent type at all closely.

Closed anticlinal fold.—A closed anticline is one in which the limbs are pressed closely together. With reference to position of axial plane a closed fold may be upright, overturned, or recumbent. A diagram of an upright closed anticline is shown in Figure 9, and a photograph of one in Figure 10. This is the central part of a much larger fold, several of which are associated here on the flank of a very much larger anticline. For several feet from the crest the strata are parallel, as they are continuously in the carinate fold. A short distance from the top, however, the strata begin to diverge. This fold is in the midst of a folded area, in the thin beds of the Simpson formation in the Arbuckle Mountains, one-fourth mile below Crusher, Oklahoma. No folds as close as this were found in the Great Lakes region, though several approach the closed condition.

Open anticline.—An open anticline is one in which the strata spread widely from the axial plane. Open folds may have the axial plane vertical or inclined. In Figure 11 a diagram is given of a gentle, open fold. The strata swing up in broad, open curves, and the dip is slight

[1] Bailey Willis, *op. cit.*, p. 221.

[2] C. R. Van Hise, *Sixteenth Ann. Rept. U.S.G.S.*, Part I (1895), pp. 581–843.

from the axis on either side. The photograph of such an anticline is shown in Figure 12. It is in the east bank of Big Creek, 3 miles south-

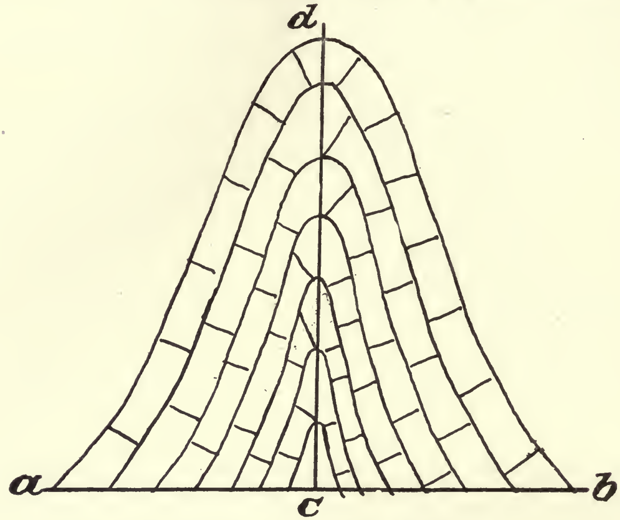


FIG. 9.—Diagram of a closed anticline

FIG. 10.—Closed anticline in Simpson formation near Crusher in the Arbuckle Mountains, Okla.

east of Painesville, Ohio. The fold is 60 feet wide, has a rise of $4\frac{1}{2}$ feet at the crest, and the dip is 12° on either side. The strike of the beds,

of N.35°W., and the direction of the axis, are well shown by the fall of the creek over the southwest limb. A sandy bed 15 inches thick in the midst of the shales is the cause of the fall, and this resistant bed stands out near the base of the bank, showing clearly the form of the fold. A large number of folds of this type were found, some larger, some smaller.

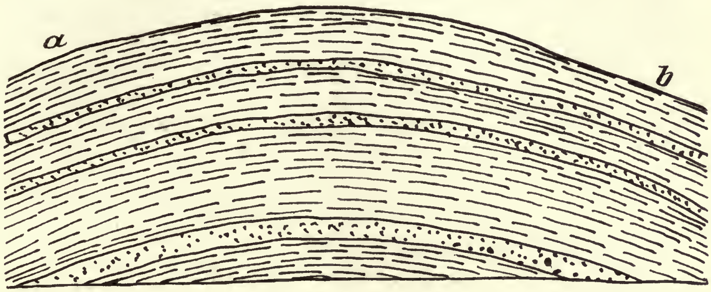


FIG. 11.—Diagram of a gentle open fold

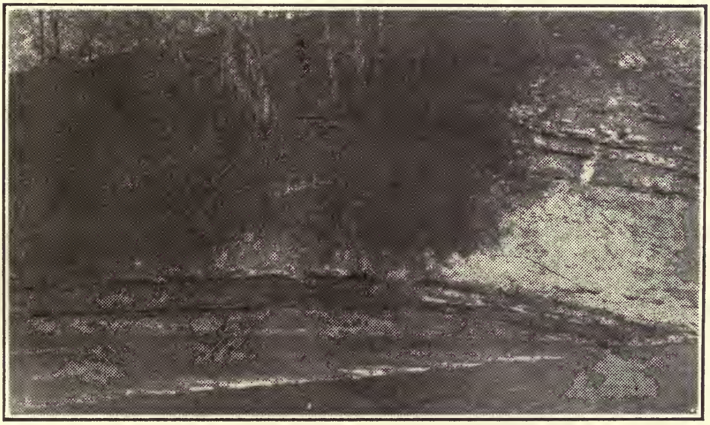


FIG. 12.—Photograph of a gentle open fold along Big Creek, near Painesville, Ohio.

Most of the large, open ones seem to belong to the earlier periods of folding, for in connection with the large open folds no evidence was found to indicate that any of them were as recent as the glacial period.

Dome.—A dome is an anticline in which the strata dip in all directions from the center, or one with quaquaversal dip. A dome may be either circular or elongate. No domes were studied in the eastern area, but one was found in the Arbuckle Mountains of Oklahoma, occurring

in the Arbuckle limestone at the head of Falls Creek (Figs. 13 and 14). Numerous larger domes occur in the Henry Mountains of Utah,[1] in the Piedmont region of Maryland,[2] and in eastern Wyoming[3]—the Black

FIG. 13.—An eroded dome in the Arbuckle limestone near the head of Falls Creek, Arbuckle Mountains, Okla.

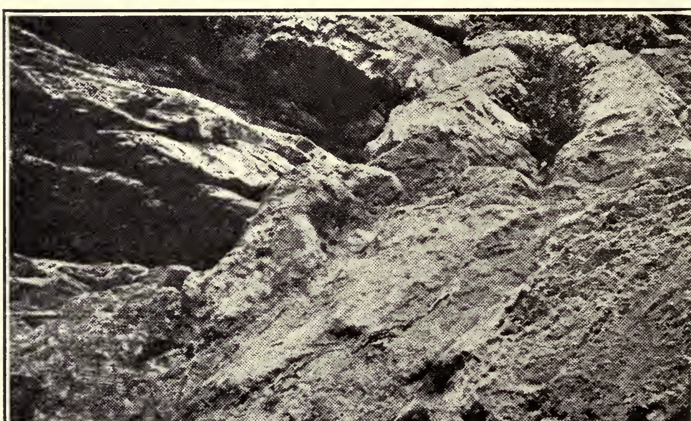


FIG. 14.—A view of the dome in Figure 13 taken across the front foreground in the bed of the creek. The deep hole at the left is in the crest.

[1] G. K. Gilbert, "Henry Mountains," *U.S.G.S.* (1877), Plates II and IV.

[2] E. B. Mathews, *Johns Hopkins University Circular*, New Series, No. 7 (1907), pp. 27–34.

[3] *Sundance Folio*, No. 127 (1905), "Structure Section Sheet."

Hills themselves being a large dome.[1] A dome of the elongate type, truncated by erosion, occurs in the Niagara limestone at Stony Island. This dome, in the southern part of Chicago, was an island at the late stage of Lake Chicago (the predecessor of Lake Michigan), when the outlet was to the southwest through the Des Plaines and Illinois rivers.

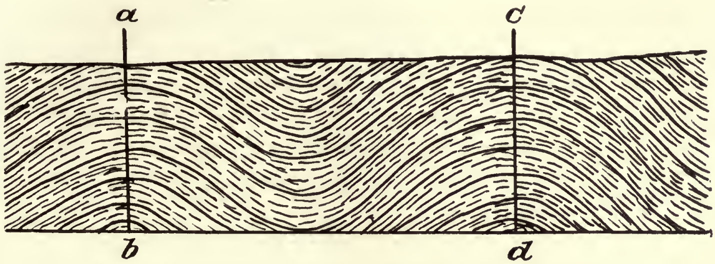


FIG. 15.—Diagram of a syncline between two anticlines

FIG. 16.—Syncline between two anticlines near Andover, Ohio

Syncline.—The syncline is the reverse of an anticline. According to Gilbert the strata in it dip in two directions toward the axis.[2] A single stratum dipping from both sides toward the axial plane forms a basin. And as the top of the anticline is called the crest, so the bottom of the syncline is called the trough. As in anticlines, so in synclines the axial planes may be vertical or inclined, and the fold may be open

[1] N. H. Darton, *Prof. Paper No. 65* (1909), p. 62.

[2] G. K. Gilbert, *Amer. Jour. Sci.*, 3d Ser., XII (1876), 21.

or closed. Figure 15 shows a diagram of a syncline between two anticlines. The axes of the anticlines are marked by the lines *ab* and *cd*. The axial plane of the syncline lies about halfway between. There are three small anticlines with two intervening synclines on the north side of a small stream at the southern edge of the Andover quadrangle, Ohio. They are upstream a few rods east of the Lake Shore and Michigan Southern Railway. A photograph of one of these synclines and two of the anticlines is shown in Figure 16. While several synclines were found, there were very few as compared with the number of anticlines.

Isoclinal or carinate folds.—When a series of folds is so closely compressed that the strata in the limbs are all parallel, they are called isoclinal, and carinate is the name given to a single fold of this type. No isoclinal folds were found.

Anticlinoria and synclinoria.—When the large anticlines and synclines have within them a series of smaller folds, they are called anticlinoria and synclinoria. Compound folds of this type are found in the Arbuckle Mountains,[1] but the larger ones are far too great in extent to get within the compass of a photograph. However, both in these mountains and in the Wichitas, smaller anticlinoria and synclinoria commonly have plunging axes, so the structure is shown by the edges of the strata that protrude in the plateaus. (See Fig. 21.) In the eastern area near the Great Lakes, anticlines and synclines are associated in a number of places, but not in the form typical of the anticlinoria and synclinoria. A part of a series of anticlines and synclines is seen in Figure 16. The fold shown in Figure 8 is adjacent to a larger anticline which has another sharp fold at the opposite end of it. Other examples of the association of anticlines and synclines are found along Elk Creek near Girard, Pennsylvania. In these instances, however, no larger fold seems to dominate them to give them the form of anticlinoria or synclinoria.

Monoclinal fold.—"A monoclinal fold is a double flexure, connecting strata at one level with the same strata at another level."[2] It has one less flexure than the anticline. Figure 17 shows a diagram of a monoclinal fold in which the double flexure, marked by the lines *cd* and *ef*, joins the strata above with the same strata at the right below. A fold of this type is shown in Figure 18. This fold is in the flaggy Chemung sandstones and shales along Sixteen Mile Creek, three-fourths of a mile northwest of North East, Pennsylvania. It deforms the fourteen-

[1] C. A. Reeds, *Okla. Geol. Surv. Bull. 3* (1910), pp. 51–53.

[2] G. K. Gilbert, *Amer. Jour. Sci.*, 3d Ser., XII (1876), 21.

foot terrace, and the loose shales at the top are uneroded. The monoclinal fold so common in the Colorado plateaus[1] is uncommon in this area, only a few others having been found.

The term monoclinal has been used with two other distinct meanings. The most common use is to express the structure of the rocks

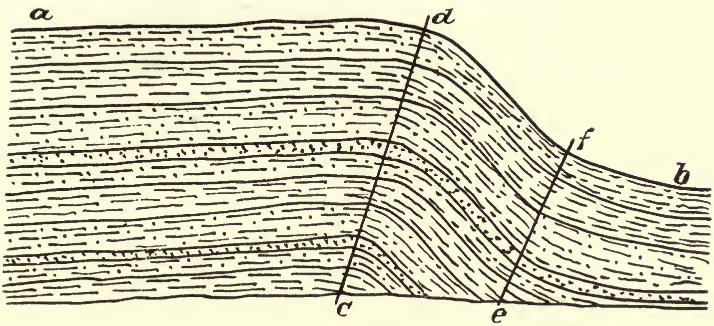


FIG. 17.—Diagram of a monoclinal fold

FIG. 18.—A monoclinal fold near North East, Pa.

in an area in which the formations of a series are inclined in a single direction, irrespective of the manner in which the dip was acquired. Thus the structure on one side of an eroded dome is called a monocline.[2] The structure of the eastward dipping rocks of the Connecticut Valley

[1] G. K. Gilbert, *ibid.*, p. 21.

[2] *Belle Fourche Folio, South Dakota* (1909), p. 5.

is called monoclinal.[1] The ridges formed by the resistant formations on one side of an eroded anticline are called monoclinal ridges.[2] The third sense in which the term monoclinal has been used is to describe a series of folds in which the axes all are parallel. Van Hise has called a series of folds with parallel axial planes monoclinal folds.[3] "Homocline" has been suggested by R. A. Daly as a substitute for monocline. He says:

> For convenience the word homocline will be used as a general name for any block of bedded rocks all dipping in the same direction. The writer is inclined to follow the general, though not universal usage which defines monocline as a one-limbed flexure in strata, which are usually flat-lying except in the flexure itself. A homocline may be a monocline, an isocline, a tilted fault block, or one limb of an anticline or syncline.[4]

This seems simply a multiplication of terms in suggesting another one for the most common usage for monocline. Monoclines readily could be distinguished as to origin by one of the prefixes tilt-, syn-, anti-, block-, or fault-.

MINOR FOLDS IN ASSOCIATION WITH MAJOR FOLDS

General relations and direction of axes.—In areas of folded rocks, smaller folds are commonly associated with the larger folds, and not infrequently folds of several orders are found together. Bascom has recognized folds of four orders associated in the Piedmont district of Pennsylvania.[5] The minor folds may occur on or among the major ones, or they may occur adjacent to the major ones, on either or both sides. With reference to the trend of axes, in some instances the axes of the minor folds are approximately parallel with those of the major ones. Mathews and Miller describe an area in north central Maryland in which the minor sharp folds are parallel with the major open ones.[6] This parallelism seems to indicate that the minor folds are related definitely to the major folds. Second, the axes of the minor folds may be transverse to those of the major folds. Those mentioned above, described by Bascom, are of this type. Here the major and minor folds seem unrelated. And third, the direction of axes of minor folds

[1] Chamberlin and Salisbury, *Earth History*, III (1906), 11.

[2] J. W. Powell, *Amer. Jour. Sci.*, 3d Ser., XII (1876), 416.

[3] C. R. Van Hise, *Ann. Rept. U.S.G.S.*, XVI, Part I (1895), 621; Fig. 134, 658; and Fig. 148, 801.

[4] R. A. Daly, *Canada Dept. Mines Geol. Surv., Mem. 68* (1915), p. 53, note.

[5] F. Bascom, *Bull. Geol. Soc. Amer.*, XVI (1905), 306–8.

[6] E. B. Mathews and W. J. Miller, *Bull. Geol. Soc. Amer.*, XVI (1905), 362.

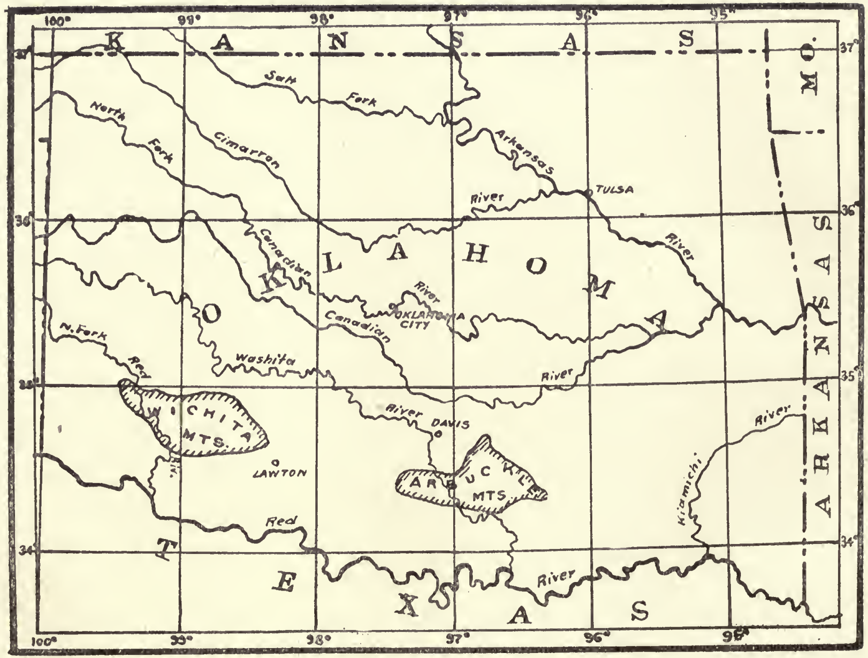


PLATE II

General Map of Arbuckle and Wichita Mountains, Okla.

may be extremely variable, making their relation to the major folds uncertain. In describing the structure of southeastern Alaska, Brooks says the main trend of the major structures is northwest and southeast, but the axes of the minor folds are extremely variable in direction.[1]

Minor folds in the Wichita and Arbuckle mountains of Oklahoma.—To show some of the relations of minor to major folds, a few illustrations will be given from the Arbuckle and Wichita mountains of Oklahoma. These mountains are in two separate groups in the southern part of the state, the Wichitas being about 60 miles northwest of the Arbuckles. (See Plate II.) Each group is about 60 miles long and about twice as long as wide, the longer axes extending in a general east-west direction. The Arbuckles are the lower, the highest part, at the northwest, rising about 400 feet above the surrounding plains to a total of about 1,300 feet. The highest peaks in the Wichitas rise about 1,500 feet above the plain, to a total height of a little less than 2,500 feet.[2]

Igneous rocks.—Both the Arbuckle and Wichita mountains consist of central masses of igneous rocks surrounded by great thickness of sedimentary formations.

In the Arbuckle Mountains there are three areas of igneous rocks. A large area in the southeastern part, of about 148 square miles, consists chiefly of granite with minor amounts of quartz-monzonite and dikes of diabase, aplite, and pegmatite. The other two areas are comparatively small ones, together being about 7 square miles in extent, in the northwestern part of the mountains.[3] These areas consist of porphyry with some basalt and diabase dikes. The predominance of acidic rocks in the Arbuckle Mountains is marked, as the basic type is limited largely to dikes.

In the Wichita Mountains the igneous rocks form a large elongate central mass around which are numerous scattered areas, particularly to the southwest and northwest. While granites and porphyries predominate, there are, besides the dikes of basalt and diabase, very large areas of gabbro, so there is a very much larger amount of basic rock in the Wichitas than in the Arbuckles. In both groups of mountains the igneous rocks are pre-Cambrian in age. Against these massive igneous rocks the sedimentary formations have been folded.

[1] F. H. Brooks, *U.S.G.S. Prof. Paper 31* (1904), p. 29.

[2] J. A. Taff, *U.S.G.S. Prof. Paper 31* (1904), p. 54.

[3] C. A. Reeds, *Okla. Geol. Surv. Bull. 3* (1910), pp. 31–32.

TABLE I

PALEOZOIC FORMATIONS OF THE ARBUCKLE MOUNTAINS, OKLAHOMA

(Modified from Wallis)[1]

System	Formations	Thickness
Permian	Red beds	....
Pennsylvanian	Franks conglomerate	0–500′
Mississippian	Caney shale	(Max) 1600′
	Sycamore limestone	0–200′
Devonian	Woodford chert	(Max.) 650′
	(*Hiatus*)	
	Bois d'Arc limestone	0–90′
	Haragan marl	0–166′
Silurian	(*Hiatus*)	
	Henryhouse shale	0–223′
	(*Hiatus*)	
	Chimneyhill limestone	0–53′
	Sylvan shale	60′–300′
Ordovician	Viola limestone	500′–700′
	Simpson formation	1200′–2000′
	Arbuckle limestone	4000′–6000′
Upper Cambrian	Arbuckle limestone	
Middle Cambrian	Reagan sandstone	0–500′

Sedimentary rocks.—In the Arbuckle Mountains, surrounding the pre-Cambrian igneous rocks, and resting unconformably upon them, is a series of sedimentary beds, 10,000 or more feet in thickness. The maximum for all the formations totals over 12,000 feet. These sediments belong to the Paleozoic. To the north, west, and southwest lie the Permian Red Beds. At the southeast the Cretaceous overlaps and extends upon the granite, covering all older formations. A table showing the formations extending from the Middle Cambrian through Permian is given in Table I. Sedimentation was almost continuous from Middle Cambrian to near the close of the Mississippian, there being but three small breaks before the marked one between the Mississippian and Pennsylvanian. Toward the end of the Mississippian the area was uplifted, and the rocks were folded and faulted. Then these folded rocks were eroded almost to a peneplain before the Franks conglomerate of Pennsylvanian age was deposited. A second period of folding and erosion followed, making the Permian Red Beds unconformable upon the edges of all the older rocks. While all the

[1] B. F. Wallis, *Okla. Geol. Surv. Bull. 23* (1915), p. 32.

formations from Middle Cambrian to Upper Mississippian were deformed together, and all are involved in the larger structures, the minor folds occur within the limits of certain formations. As illustrations will be used only from the Arbuckle and Simpson, only these two formations will be described.

The oldest sedimentary formation in the region, the coarse Reagan sandstone, is succeeded conformably by the Arbuckle limestone. This is the most competent formation in the region. It is heavy bedded, and has the great thickness of 4,000 to 6,000 feet. Most of the beds are a foot or more in thickness, and some are over 10 feet. In general the texture varies from fine even granular to compact, but some parts are coarsely crystalline, and some rather shaly members occur near the top.

The Simpson formation reaches a thickness of 1,200 to 2,000 feet. The lower part consists of sandstone with shales, then limestone and more sandstone, and thinly bedded shaly limestones above. So in contrast with the Arbuckle limestone, the Simpson is relatively weak and incompetent. In the Wichita Mountains the sedimentary formations have much the same characteristics as in the Arbuckles in so far as they are exposed, but the Red Beds still cover all but the Reagan, Arbuckle, and a little of the Viola.

Structure of rocks.—As noted before, all the Paleozoic formations except the Pennsylvanian and Permian were deformed together, the deformation including intense folding and faulting. The general trend of the larger folds is northwest-southeast, and they are several miles in width. Upon them are the smaller folds of one or more orders. On one of the large folds, C. A. Reeds[1] has recognized ten smaller longitudinal ones, and several still smaller transverse ones of a third order. In both groups of mountains the Arbuckle limestone exhibits these minor folds of several orders on the major ones. These major folds, many of which have plunging axes, have been truncated by erosion, and the edges of the strata in these truncated folds show clearly on the plateaus.

Types of folds.—As indicated above, some types of folds are found in the folded mountain areas that do not occur in the eastern lake region. The two types already illustrated—the dome, and the closed fold—will be treated more in detail, and some plunging folds illustrated and described.

The dome shown in Figure 13 occurs in the channel near the head of Falls Creek, where a good section has been exposed by the stream

[1] C. A. Reeds, *Okla. Geol. Surv. Bull. 3* (1910), pp. 51–53.

cutting across it. It is a very close and conical fold to be formed in a heavy-bedded formation, and shows well how abruptly parts of this thick-bedded limestone have been folded. The bed at the left is 4 feet 3 inches thick. Another picture was taken across the eroded north end of the dome across the right foreground in Figure 13. This view is given in Figure 14, in which the abrupt curve in these heavy beds is shown. The stream has eroded a deep hole at the left from the crest of the fold. This is the most abrupt one of a series of small folds found on the large Arbuckle anticline.

Another type of fold in a different relation occurs one-fourth mile below Crusher, on the southeast side of the Washita River. Here the

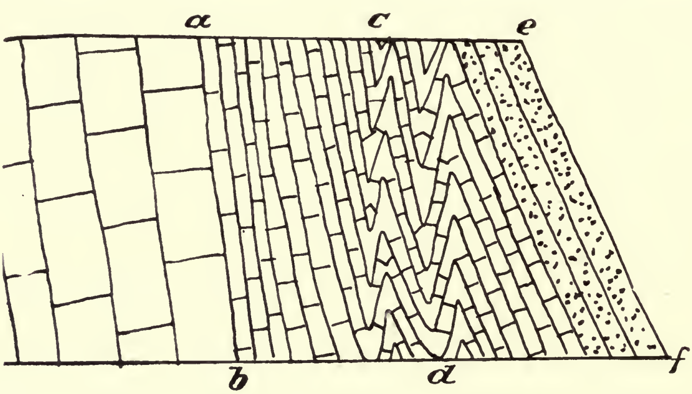


FIG. 19.—Diagram of a part of southwest limb of Arbuckle anticline, showing folds in the thin-bedded Simpson formation. The heavy beds at the left represent the Arbuckle limestone.

minor folds are on the southwest limb of the same large Arbuckle anticline. The center of the large fold and the inner part of the southwest limb are occupied by the heavy beds of the Arbuckle limestone, and succeeding these toward the southwest are the thin beds of the Simpson. These relations are shown in Figure 19. The sharp folds shown in the diagram are in the thin beds in the Simpson. The beds to the right of the fold are the sandstones of the Simpson, while the thick beds at the left represent the Arbuckle limestone. This illustrates the difference in the response to the compressive stresses in the two formations. In the Arbuckle the readjustment has taken place between the heavy beds, while in the Simpson it has taken place across the thin beds, throwing these thin beds into acute folds. Figure 10 shows the central part of one of these close folds. These folds are in the position on the large

anticline in which there is the maximum of readjustment, for it is least at the crest of an anticline and the trough of a syncline, and most at intermediate points on the limb.[1] These minor folds not only show the difference in the response of the two formations, but they are a measure, in part at least, of the readjustments that have taken place between the beds in the Arbuckle limestone. Leith has stated succinctly this relation the folds in the weaker formations bear to the movements between the more resistant ones, as follows:

Rocks within our field of observation are of varied competence. It follows then that in any folded area the structures of the weaker rocks are controlled by the folding of the stronger beds, and these tend to assume the "parallel" type of fold, in which the readjustment is between the beds rather than in them. This readjustment or slipping is concentrated in the intervening weaker layers. The structures of the weaker layers indicate the direction of the readjustment, and thus something of the structure of the competent beds.[2]

More common than the dome and the closed fold are those of a more open type which generally have plunging axes. Two broad open anticlines with an intermediate synclinal trough are shown in Figure 20. They occur on the north side of the Wichita Mountains, where the general dip is northward toward the left. These are minor folds on a series of much larger ones succeeding one another across the broad exposure of the Arbuckle limestone. At this locality, this formation has exceptionally heavy beds, some of them being over 10 feet in thickness.

A part of a more sharply plunging fold in the Arbuckle Mountains is shown in Figure 21, in which the beds are seen to curve around from the foreground toward the right. This plunging anticline is only one of a large number exposed over hundreds of acres of this plateau. The trees in the center of Figure 21 are on the sides of the channel of Falls Creek, near its head. A few miles to the north, the Arbuckle limestone is mineralized, and some zinc has been taken from it.

When it is realized that minor folds may be the key to the solution of major complex structures, they are invested with a new significance.

Summary of minor folds in association with major folds.—From this brief consideration of minor folds associated with major ones, it is concluded that they are worthy of careful attention and study, as they may be an important part of a major structure. They are particularly significant when occurring in the weaker strata of a series, as they then give evidence of the magnitude and nature of the differential

[1] C. R. Van Hise, *Jour. Geol.*, IV (1896), 208.

[2] C. K. Leith, *Structural Geology* (1913), p. 114.

movements in the stronger adjacent rocks, and they may give a clue to the solution of the complex major structures.

FIG. 20.—A gentle syncline between two anticlines in very heavy beds of Arbuckle limestone on the north side of the Wichita Mountains.

FIG. 21.—Edge of strata in an anticline plunging to the left, near head of Falls Creek, Arbuckle Mountains.

FOLDS IN THE MIDST OF HORIZONTAL OR GENTLY DIPPING STRATA

Location and area.—This study of minor folds began with a few small ones in the vicinity of Meadville, Pennsylvania. Part of these

folds had been described earlier.[1] From this locality the study was carried northward to Lake Erie, thence westward into Ohio and eastward into New York. Most of the study was limited to a strip 15 to 30 miles wide, along the south side of Lake Erie, extending from Cleveland, Ohio, to Dunkirk, New York, a distance of 140 miles. However, farther west, most of the larger streams between Cleveland and Sandusky were traversed for several miles from the lake, and points were visited in east central New York and on both sides of Lake Ontario in New York and Ontario. (See Plate I, general map.)

This strip bordering the south shore of Lake Erie is at the north end of the broad structural basin lying between the Allegheny Plateaus to the southeast and the Cincinnati Arch on the west.

There seems to have been an impression that in this area in which the rocks in general are flat-lying, no folds would be found. White says of this area:

> If there be any anticlinical and synclinal undulations at all in Erie and Crawford counties, they are so exceedingly flat that nothing short of an expensive system of measured borings, connected by instrumental surveys, would suffice to reveal their presence, measure their force and determine their direction; which by the way should be from the northeast to southwest at some angle approximately parallel to the anticlinal rolls of Clarion, Butler and Beaver counties.[2]

When some folds were found, an attempt was made to connect them with the Appalachian structure to the southeast, but it was concluded that they could not be related to the larger folds because their axes were variable, and because they were not parallel with those of the major structures to the southeast.[3] This study has brought out the fact that numerous small folds and faults exist in this region.

TOPOGRAPHY OF THE AREA

This area bordering the south side of Lake Erie is naturally divided into two provinces—the Lake Plain and the Upland.

The Lake Plain.—The Lake Plain is a narrow strip varying from 4 to 6 miles in width. The elevation of this plain above the lake along its northern edge is variable. Northeast of Cleveland there is a 25-foot bluff, while north of Geneva, 12 miles west of Ashtabula, there is no cliff. For most of the distance eastward the cliff varies from 25 to

[1] Smallwood and Hopkins, *Bull. Syracuse Univ.*, 4th Ser., No. 1 (1903), pp. 18–24.

[2] I. C. White, *Second Geol. Surv. Pa.*, Rept. Q^4 (1881), p. 45.

[3] Smallwood and Hopkins, *op. cit.*, pp. 18–24; and I. C. White, *op. cit.*, p. 45.

60 feet. However, at points northwest of Girard and north of North East, Pennsylvania, it has a height of more than 125 feet. Along its southern margin this plain rises from 100 to 200 feet above the lake. The general slope of the plain toward the lake is 20 to 40 feet per mile, though some parts of it are very flat, as in the area west of Painesville, Ohio. The plain is trenched by several large streams crossing it, the most important of which are the Cuyahoga, Chagrin, Grand, and Ashtabula rivers, and the Conneaut, Elk, Walnut, Mill, Sixteen Mile, Twenty Mile, Chautauqua, and Canadaway creeks. Most of these streams cross the plain through valleys with steep banks which frequently are 80 feet or more in height. Some of the streams have widened their valleys to a fourth- or a half-mile, and a few have locally widened them still more. Along the channel numerous terraces occur at various intervals above the flood plains. Between the major streams numerous small ones cross the plain. A few of these have deep channels, but most of them flow through slight depressions.

The Upland—The northern part of this Upland forms the divide between the streams tributary to Lake Erie and those flowing south. From Cleveland east to Girard the divide is about 25 miles south of the lake shore. Eastward from Girard it is less than 10 miles from the lake. At the inner edge of the Lake Plain there generally is an abrupt slope in the form of a lake cliff marking a former higher level of the lake. At the west the divide usually is flat, with elevations reaching above 1,300 feet (Lake Erie is 573′ A.T.). Toward the east the divide rises to over 1,600 feet, or about 900 feet above the lake, though some of the hills in the Clymer quadrangle have elevations above 1,800 feet. The rise from the Lake Plain is less marked at the west than in the east. Five miles west of Westfield, New York, the rise is 500 feet in three-fourths of a mile.

The Upland is very prematurely dissected, or in a youthful stage of erosion. The larger streams tributary to the lake have trenched their post-glacial valleys through glacial till deeply into the bedrock. The banks along many of the streams rise abruptly 80 or 100 feet above the valley floor, and in the gulf south of Westfield the banks rise 400 feet above the stream. As in the Lake Plain, so in the Upland, terraces with varying intervals occur in these valleys. The large streams forming a part of the southward drainage flow for the most part through broad, flat valleys, from which hills rise by several easy stages to heights of from 100 to 500 feet. Locally, where streams are impinging against the sides of old valleys, and in a few places where there is great inequality

in hardness of rocks, as at Thompson's ledge, twelve miles southeast of Painesville, Ohio, steep slopes exist. Some of the small tributaries to these larger streams have cut deep valleys into hillsides, exposing thick sections of bedrock.

TABLE II

SHOWING PENNSYLVANIAN AND MISSISSIPPIAN FORMATIONS FOR PENNSYLVANIA, AND DEVONIAN, SILURIAN, AND ORDOVICIAN FOR NEW YORK

(After Clarke and Schuchert,[1] and White[2])

System	Formation	System	Formation
Pennsylvanian	Sharon or Olean conglomerate	Silurian	Manlius limestone
			Rondout waterlime
			Salina beds
Mississippian	Shenango beds		Guelph dolomite
	Meadville beds		Lockport limestone
	Sharpsville sandstone		Rochester shale
	Orangeville shale		Clinton beds
	Cussewago beds		Medina sandstone
	Riceville shale		Oneida conglomerate
Devonian	Chemung beds	Ordovician	Richmond beds
	Portage beds		Lorraine beds
	Genesee shale		Utica shale
	Tully limestone		Trenton limestone
	Hamilton beds		Black River limestone
	Marcellus shale		Lowville limestone
	Onondaga limestone		Chazy limestone
	Schoharie grit		Beekmantown limestone
	Esopus grit		
	Oriskany beds		
	Kingston beds		
	Becraft limestone		
	New Scotland beds		
	Coeymans limestone		

STRATIGRAPHY

In the region along Lake Erie the exposed rocks extend in age from Upper Devonian to Lower Pennsylvanian. However, as other areas of

[1] J. M. Clarke and C. Schuchert, *Science*, New Ser., X (1899), 876.

[2] I. C. White, *Second Geol. Surv. Pa.*, Rept. Q^4 (1881), pp. 55, 56.

older rocks were visited farther east and northeast, a few of the older formations will be characterized briefly. To indicate their relative position, the succession is shown in Table II. In this table the Pennsylvanian and Mississippian are for northwestern Pennsylvania, and the Devonian, Silurian, and Ordovician for New York.

ORDOVICIAN FORMATIONS

Beekmantown limestone.—This formation and the pre-Cambrian syenite on which it rests in all the exposure of the latter in the quadrangle, were seen near the west edge of the Little Falls quadrangle at Middleville, 8 miles north of Herkimer, New York. About 200 feet of Beekmantown are exposed at this locality.[1] The Beekmantown is a gray, sandy dolomitic limestone. The thickness of the beds varies from 3 inches to 2 feet. Some very sandy beds 4 to 12 inches in thickness were observed in the ravine north of Middleville. Some low open folds occur in this formation similar to those in the following one.

Lowville limestone.—The Chazy formation being absent in this Little Falls area, there must be disconformity between the Beekmantown and the Lowville.[2] The Lowville is a medium to thin-bedded pure gray limestone, which near Middleville has a thickness of only about 20 feet. Cushing shows two good exposures of it in Plates 5 and 6, in Bulletin 77 of the New York State Museum series. In the latter of these two plates the low folds are well shown.

Trenton limestone.—The thin formation of limestone and shale above the Lowville—the Black River—was not exposed at the two areas visited in the Remsen quadrangle. The Trenton was seen at Gravesville near the southern edge of the Remsen quadrangle, 20 miles northwest of Herkimer, and at Prospect, 4 miles northwest of Gravesville. "In general this formation may be said to be made up of thin bedded, dark bluish compact limestones with thin shaly partings."[3] The Trenton limestone is very fossiliferous.

The formations in the Upper Ordovician will not be mentioned except to note that the next formation, the Queenston shale, may in part be equivalent to the Richmond.[4]

Queenston shale.—The Queenston shale is exposed at the lower end of the Niagara Gorge at Queenston, Ontario, whence it derives its

[1] H. P. Cushing, *New York State Mus. Bull. 77, Geol. 6* (1905), p. 28.

[2] H. P. Cushing, *ibid.*, pp. 27–30.

[3] W. J. Miller, *New York State Mus. Bull. 126* (1909), p. 17.

[4] E. M. Kindle and F. B. Taylor, *Niagara Folio,* No. 190 (1913), p. 6.

name. It is exposed eastward along the south shore of Ontario across the Niagara quadrangle, and in the valleys of the streams flowing into the lake. It is particularly well exposed in the gorge of Eighteen Mile Creek, two miles south of Olcott, New York. The same type of formation, with colors and physical characteristics the same, is exposed on the north shore of Lake Ontario to the east of Burlington, both along the shore and in valleys of streams tributary to the lake. The Canadian geological map shows that the Silurian extends around the west end of Lake Ontario and on the north side well up toward Toronto.[1] The Queenston formation consists chiefly of friable shale with some intercalated thin sandstone beds. The predominating color is red, but beds of green and gray shales and sandstone occur, interspersed through the red shales. The total thickness, determined from deep wells, is 1,200 feet, only 300 feet of which are exposed.[2]

Passing over the rest of the Silurian formations and the Lower and Middle Devonian, the Portage group in the Upper Devonian will next be considered. (See basal part in center of Table III.)

TABLE III

UPPER DEVONIAN AND LOWER MISSISSIPPIAN FORMATIONS FOR OHIO, PENNSYLVANIA, AND NEW YORK

System	Ohio[3]	Pennsylvania[4]	New York[5]
Lower Mississippian	Sunbury shale	Orangeville shale	
		Corry sandstone	Knapp formation
	Berea grit		
		Cussewago sandstone	
	Bedford shale		
		Riceville shale	Oswayo formation
Upper Devonian	Cleveland shale		
		Chemung	Cattaraugus Chemung
	Chagrin formation	Girard shale	
	Huron shale	Portage[6]	Portage beds[7]

[1] *Atlas of Canada*, No. 5, "Geology, East Sheet."

[2] Kindle and Taylor, *op. cit.*, p. 5.

[3] C. S. Prosser, *Geol. Surv. Ohio Bull. 7*, 4th Ser. (1905), p. 4.

[4] I. C. White, *Second Geol. Surv. Pa.*, Rept. Q^4 (1881), pp. 117–20.

[5] *Elkland-Tioga Folio* (1903), p. 5; *Warren Folio* (1910), p. 3; C. Schuchert, *Bull. Geol. Soc. Amer.*, XX (1908), 548; L. C. Glenn, *N.Y. State Mus. Bull. 69* (1903), pp. 967–95.

[6] J. M. Clarke, *N.Y. State Mus. Bull. 69* (1903), p. 853.

[7] D. D. Luther, *N.Y. State Mus. Bull. 69* (1903), pp. 1000–1029.

UPPER DEVONIAN FORMATIONS

Portage group.—White gives the name of Portage to the oldest rocks exposed in northwestern Pennsylvania. Coming from beneath the lake 2 miles east of the Ohio state line, they rise until 475 feet are exposed at the New York state line.[1] These rocks consist of gray shales and flaggy sandstones. The layers of sandstone usually are 12 inches or less in thickness, occasionally 2 feet. White follows Hall's earlier identification of these rocks as Portage.[2] Clarke, however, says there is no Portage in northwestern Pennsylvania.[3]

The Portage group has been restudied by Clarke and Luther[4] in its type section at Portage on the Genesee River and in its general exposures, and they have made a detailed geological map for the group in western New York, which shows the rocks of this group extending from Seneca Lake in a strip with irregular borders to the shore of Lake Erie. According to this map the most westward exposure of the Portage extends a little west of Westfield, New York. As there is a general dip of the formations here toward the southwest, only a marked anticline or a fault would expose the Portage again in Pennsylvania.

The Portage group, as recently described, consists of nine formations shown in the following table, in which the thickness of each formation and the total thickness are given.[5]

TABLE IV

PORTAGE GROUP

(After Clarke and Luther)

Formations	Thickness
1. Passage shales	3′
2. Middlesex black shale	32′
3. Cashaqua shale	165′
4. Rhinestreet black shale	53′
5. Hatch shale	203′
6. Grimes sandstone	25′
7. Gardeau shales and flags	372′
8. Portage sandstones	187′
9. Wiscony shale	167′
Total	1207′

[1] I. C. White, *Second Geol. Surv. Pa.*, Rept. Q^4 (1881), pp. 119–20.

[2] J. Hall, *Nat. Hist. N.Y. 4th Dist.*, Part IV (1843), p. 238.

[3] J. M. Clarke, *N.Y. State Mus. Bull. 69, Paleon. 9* (1902), p. 853.

[4] J. M. Clarke, *ibid.*, pp. 1000–1029, and Geol. Map; also J. M. Clarke and D. D. Luther, *N.Y. State Mus. Bull. 118, Paleon. 18* (1908), pp. 1–69.

[5] Clarke and Luther, *ibid.*, p. 1010.

This total thickness is a little above Hall's earlier estimate of over 1,000 feet.[1] The foregoing table shows the general character of the Portage in New York. If the northwest dip continues constant, so that none of the Portage group is exposed along the lake in Erie County, Pennsylvania, the rocks there formerly called "Portage" must be younger. Dr. Clarke has reached this conclusion, for he says: "The 'Portage' and 'Girard Shales' of Erie County, Pennsylvania, are later than Portage time."[2] Also, Chemung brachiopods have been collected near the lake north of North East, Pennsylvania, in what was considered the lower part of the "Portage" for that locality.[3]

Huron shale.—The position of the Huron shale in northeastern Ohio is in question. The name was given to the black bituminous shales exposed along the Huron River. Prosser took the position that the Huron west of Cleveland is at least in part synchronous with the Chagrin to the east.[4] If the two are in contact at all, the darker lower shales may then be called Huron.

Girard shales.—The Girard shales appear above the lake a short distance east of the Ohio state line, and the basal beds rise to 475 feet above it at the New York state line. They are gray and grayish-blue shales containing a few thin beds of sandstone, and have a thickness in Pennsylvania of 225 feet.[5] They are very friable and easily eroded. In some localities they contain large calcareous concretionary lenses, while in others, cone-in-cone is common. The relation of the Girard shales to the Chagrin is seen in the following statement: "The Girard shales lithologically are very similar to the lower part of the Chagrin formation as seen in northeastern Ohio, of which they are the eastern continuation.[6] They now are thought to be Chemung in age.[7] They contain few fossils.

Chagrin formation.—The Chagrin, or Erie, shales are soft bluish gray, containing a few thin sandstone beds and locally calcareous beds. The upper part of the Chagrin is considered Chemung.[8] As just noted, the lower part is equivalent to the Girard shales. The Chagrin

[1] J. Hall, *op. cit.*, p. 238.

[2] J. M. Clarke, *Bull. Geol. Soc. Amer.*, XIV (1902), 536.

[3] D. D. Luther, *N.Y. State Mus. Bull. 69, Paleon. 9* (1903), p. 1028.

[4] C. S. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912), pp. 515, 519.

[5] I. C. White, *Second Geol. Surv. Pa.*, Rept. Q^4 (1881), pp. 118, 119.

[6] C. S. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912), p. 451.

[7] C. S. Prosser, *ibid.*, p. 451.

[8] C. S. Prosser, *op. cit.*, pp. 462–64.

formation is widely distributed in northeastern Ohio, and extensive exposures of it may be seen in nearly all the valleys of the rivers and larger creeks.

Chemung formation.—The Chemung of northwestern Pennsylvania is described as composed of alternate groups of shale and sandstone, with a thickness of 325 feet.[1] If the rocks called "Girard shales" and "Portage" are also Chemung, the total thickness would be 1,025 feet. As noted above, the Chemung is continued into Ohio as the upper part of the Chagrin formation. Hall says of the Chemung that "this group consists of a highly fossiliferous series of shales and thin-bedded sandstones, sometimes in well-defined and distinct courses, and an infinite variety resulting from the admixture of the two ingredients."[2] The colors are green, gray, and black. The formation becomes pebbly and conglomeratic toward the top. The Chemung has a thickness of 1,120 feet in the Warren quadrangle.[3] This quadrangle is in the northern part of Warren County, Pennsylvania, which is east of Erie County in the same state, and south of Chautauqua, the most western county of New York.

Cleveland shale.—In northeastern Ohio the uppermost formation recognized in the Devonian is the Cleveland shale.[4] It is a carbonaceous shale of brownish-black color and homogeneous texture. In thickness it varies from 30 to 200 feet.[5] East of Cleveland the formation decreases in thickness and disappears in Trumbull and Ashtabula counties.[6] Edward Orton includes the Cleveland, Erie (Chagrin), and Huron shale all under the Ohio shale.[7]

Cattaraugus formation.—In southwestern New York and in northwestern Pennsylvania, the Cattaraugus is the name given to a thick formation of Upper Devonian age next above the Chemung.[8] In the Gaines quadrangle in northern Pennsylvania this formation consists of red, gray, and green shales alternating with brown and green sandstones. Northward, in southern New York, several conglomerate mem-

[1] I. C. White, *op. cit.* (1881), p. 117.

[2] J. Hall, *Nat. Hist. N.Y. 4th Dist.*, Part IV (1843), p. 252.

[3] *Warren Folio*, No. 172 (1910), p. 3.

[4] C. S. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912), pp. 16–21.

[5] E. Orton, *Geol. Surv. Ohio, Econ. Geol.*, VI (1888), 26.

[6] C. S. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912) pp. 509–14.

[7] E. Orton, *Geol. Surv. Ohio, Econ. Geol.*, VI (1888), 23.

[8] L. C. Glenn, *N.Y. State Mus. Bull. 69, Paleon. 9* (1903), pp. 971–78; and *Gaines Folio*, No. 92 (1903), columnar section at back.

bers are recognized in the midst of the formation. In the Gaines area it is about 500 feet in thickness.

DEVONO-CARBONIFEROUS FORMATIONS

Under this head are classed several transitional formations which have not been definitely assigned either to the Devonian or Mississippian. Two will be noted here, the Riceville shale and the Oswayo formation.

Riceville shale.—In Crawford County, Pennsylvania, the Riceville shale consists of 80 feet of grayish-blue shales and shaly sandstone. Correlation with parts of Cleveland and Bedford shales of Ohio have been suggested.[1] The Riceville contains many fossils common in the Chemung.

Oswayo formation.—In northern Pennsylvania a series of shales and sandstones about 1,000 feet thick has been assigned to this formation, and it has been classed as Devono-Carboniferous in age.[2] In southwestern New York it is classed with the Carboniferous formations by Glenn.[3]

MISSISSIPPIAN FORMATION

Bedford shale.—Of the Mississippian formations given in Tables II and III, folds were found only in the Bedford shale, so only that one will be described. It is placed at the base of the Mississippian formations of northeastern Ohio, and succeeds the Cleveland shale, being succeeded by the Berea grit, that being correlated with the Cussewago and Corry formations of Pennsylvania.[4] The Bedford formation is extremely variable in thickness, for its top surface is very irregular, marking an unconformity between it and the Berea. It consists chiefly of bluish-gray and chocolate-colored shales with a varying amount of sandstone interspersed. In its type locality it has a thickness of 88 feet.[5]

PENNSYLVANIAN FORMATION

Sharon or Olean conglomerate.—The youngest formation in the region under consideration is the Sharon or Olean conglomerate. It has a marked unconformity at the base, and is found only on the tops of the highest hills back a considerable distance from the lake, in Ohio, Pennsylvania, and New York. It is a coarse conglomerate with white

[1] I. C. White, *Second Geol. Surv. Pa.*, Rept. Q^4 (1881), p. 97.

[2] *Gaines Folio*, No. 92 (1903), p. 2.

[3] L. C. Glenn, *op. cit.*, p. 978.

[4] C. S. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912), pp. 352, 511.

[5] C. S. Prosser, *ibid.*, p. 87.

quartz pebbles generally about one-half to three-fourths of an inch in diameter. Large parts of it commonly are strongly cross-bedded. At Thompson's Ledge in northern Ohio, it has a thickness of 80 feet;[1] northeast of Meadville, Pennsylvania, 40 feet; and in the Gaines quadrangle, in north-central Pennsylvania, 60 to 100 feet.[2] No indurated rocks younger than those of early Pennsylvanian age have been found in this area.

QUATERNARY DEPOSITS

Pleistocene.—The deposits of Quaternary age consist chiefly of glacial till, sand, and gravel. The glacial drift is very irregularly distributed. In general it is thinnest on the hilltops and thickest in the valleys, varying from nothing on the former to nearly 500 feet in the latter. The deposits of the ground moraine are very irregular in thickness, but there is still greater irregularity in the broad complex terminal moraines. Locally, extensive deposits of gravel and sand have resulted from glacio-fluvial work in the form of kames and kame terraces.

Post-glacial.—Post-glacial deposits have been formed in lakes and by streams. In small lakes some peat and much marl have been deposited, while streams have made deposits in the form of alluvial fans, flood plains, and deltas.

GEOLOGIC HISTORY

As noted above, the oldest rocks exposed in the specific area under consideration are of Upper Devonian age. However, the deep well at Presque Isle, Erie, Pennsylvania, at a depth of 4,450 feet is thought to have penetrated 170 feet of the Trenton limestone, and the general formations of the New York section intervening between the Trenton and the Chemung are represented.[3] Marine conditions seem to have been dominant in the area, from early Paleozoic until toward the close of the Mississippian. In the earlier periods limestone predominated; toward the close, clastic formations. All older formations are concealed beneath Upper Devonian. The formations of this epoch indicate shallow marine deposition with fine silt as the chief sediment, though alternating rather frequently with sand.

There seems to have been no break in sedimentation at the close of the period, and no good line of demarcation has been drawn between Devonian and Mississippian rocks. Marine deposition continued

[1] C. S. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912), pp. 286–88.

[2] *Gaines Folio*, No. 92 (1903), columnar section in back.

[3] C. S. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912), pp. 412–22.

through a large part of the Mississippian period, with clastic materials greatly predominating. Toward the close of the latter period the area was elevated, and suffered erosion before the Pennyslvanian rocks were deposited. After this erosion interval the region was depressed, and a coarse conglomerate with white quartz pebbles spread widely over the area. Above this conglomerate shales and coal were deposited, but they have been completely removed by erosion from most of the area. If Permian or younger rocks ever were deposited, all evidences of their presence have been carried away. It is thought then that this area has been above the sea ever since a time near the close of the Paleozoic.

PHYSIOGRAPHIC HISTORY

Since the Paleozoic, in the vast periods of erosion which followed, the history of this area doubtless closely paralleled that of southwestern Pennsylvania.[1] In the latter region erosion is thought to have reduced the land to a peneplain before the close of the Cretaceous, and this first great base-level is called the *Schooley Peneplain.* Succeeding uplift initiated a second cycle of erosion which nearly obliterated the former plain, developing the *Harrisburg* as the second peneplain in early Tertiary time. After subsequent uplift and erosion a third less complete peneplain—the *Worthington*—was developed toward the close of Tertiary time. A series of straths and terraces below the latest peneplain is taken to indicate still later periodic elevations of the region. The deformation of the Harrisburg or late Tertiary peneplain has been worked out in considerable detail by M. R. Campbell. He finds it has a domelike uplift, so that it is 1,600 feet higher in northern Pennsylvania and southern New York than in southeastern Pennsylvania. (See Plate III.)[2] Doubtless as many peneplains were developed in northwestern Pennsylvania as in the southwestern part of the state, but some of the evidences of them have been obliterated by the heavy deposits of glacial drift in the northern region.

The tops of the higher hills easily are recognized as remnants of a peneplain. Below these, broad flat areas of great extent seem to represent a second less complete plain. Below this broad plain, terraces of varying width can be recognized, though they are materially modified by glacial deposits. During the last period of erosion preceding glaciation, the valleys were cut from 800 to 1,000 feet below the hilltops. Accordingly, when the continental glaciers invaded this area, it was one

[1] R. W. Stone, *Rept. Top. and Geol. Surv. Com. Pa.* (1906–8), pp. 120–22.

[2] M. R. Campbell, *Bull. Geol. Soc. Amer.*, XIV (1903), 277–96.

of considerable relief. It was covered by that part of the glacier called the Grand River Glacial Lobe.[1] Glaciers had a marked effect on the topography of the area. While glacial erosion seems to have been relatively unimportant, glacial deposition and drainage changes were of great importance. Evidences of only two glacial epochs in this area have been found.[2]

Glacial erosion.—At the quarry 1 mile northeast of Meadville, Pennsylvania, planation, grooving, and striation resulted from erosion, but the glacier did not erode the rocks deeply, for evidences of former weathered surfaces exist below the plane cut by the ice. Doubtless the tops of the hills were not lowered materially by glacial erosion, but were only smoothed and rounded in contour somewhat by its action.

Glacial deposition.—Glacial deposition did affect the topography very materially. Terminal moraines with accessory kames, kame terraces, outwash plains, and ground moraines with drumlins were formed. Some of the old valleys were filled in with much drift, 200 to 300 feet of drift being common, and nearly 500 feet being reached near Meadville, Pennsylvania.[3] In the moraines the drift was deposited in rounded hills both in valleys and on uplands alike.

Drainage changes.—The effect of glaciation on the drainage systems of this area was very marked.[4] Several large northward-flowing systems were practically obliterated, and their drainage areas added to systems of the southward-flowing streams. There was then a marked shifting of the divide northward. Owing to conditions near the close of the glacial period, several of the northward flowing streams reach the lake by very peculiar courses. As the ice receded from the area toward the northeast, drainage was established westward along its southern margin, after it receded north of the divide. The southern margin remained constant at a number of places for a sufficient length of time for channels to be developed parallel with it. As a result several streams run parallel with the lake shore for a considerable part of their course. Another condition favoring this parallelism is the trend of the morainic deposits, which are about parallel with the lake shore. Because of these deposits some of the streams were deflected westward on the south side of them. Examples of this type of course are Twenty Mile, Walnut, Elk, and Conneaut creeks, and Ashtabula and Grand rivers. Thus the headwaters of the stream in Gage Gulf are but 3 miles from

[1] F. Leverett, *U.S.G.S. Mono. 41* (1902), Plate 15.

[2] F. Leverett, *ibid.*, pp. 272–74, and Plate 15.

[3] F. Leverett, *ibid.*, p. 458.

[4] F. Leverett, *ibid.*, pp. 128–44.

the lake, but it flows in a westerly direction for 9 miles, then 3 miles to the lake. From the abrupt turn at Conneaut Creek north of Albion it is but 6 miles to the lake, but from that point it goes 20 miles westward and then over 9 miles northeastward to the lake. The Grand River also runs parallel with the lake for over 20 miles within 8 miles of the shore.

Glacio-Lacustrine substage.—As the ice receded from the lake basin it was occupied by water standing at very much higher levels for a series of stages. To these various stages the names of Maumee, Whittlesey, Warren, and Dana were given. At the Whittlesey stage the water was 211 feet above the present level of Lake Erie at the New York state line.[1] Besides these higher lake stages there were numerous small ice-front lakes in northwestern New York and Pennsylvania.[2]

Post-glacial changes.—Since the glaciers receded, the streams of this area have been active. While a few of them seem to have accomplished little, most of them have cut their channels through the drift and into the bedrock beneath. Many of these channels are 80 to 100 feet in depth, while the one south of Westfield, New York, is over 400 feet in depth. In this down-cutting process, numerous terraces have been left marking the old high-stream levels. As noted above, stream deposits have been made in the form of alluvial fans, alluvial plains, and deltas.

Similarly, Lake Erie has been actively at work undercutting the cliffs along its southern margin, causing the shore to recede southward. Sediments derived by shore erosion and by transportation of streams have been deposited along the beach in bars or hooks, or carried to the deeper parts of the lake basin.

STRUCTURE OF THE ROCKS

General structure.—The rocks of the area in general appear to be flat-lying, although the distribution of formations on the geologic map shows a belted arrangement characteristic in regions with monoclinal dip. The oldest rocks are exposed along the lake, and successively younger ones toward the south. The dip of the rocks in northwestern Pennsylvania has been figured to be about 20 feet per mile southward and 10 feet per mile westward.[3] The amount of dip, however, is not constant, but increases toward the northeast.

[1] H. L. Fairchild, *N.Y. State Mus. Bull. 106* (1907), pp. 42–44.

[2] H. L. Fairchild, *ibid.*, pp. 33–41.

[3] J. P. Lesley, *Second Geol. Surv. Pa.*, Rept. Q^4 (1881), pp. 45–49.

Local structures.—In this general area of very gently dipping rocks, numerous irregularities occur in the form of small folds and faults. The faults are all thrust faults, but among the folds, besides the specific types before mentioned, several general types will be considered.

GENERAL TYPES OF FOLDS

Intra-formational folds.—While some of the folds in the region south of Lake Erie are limited to only a few feet in vertical extent, it is significant that they do not commonly show close, overturned, and recumbent types, which are very common in minor intra-formational folds. A close fold of this type, occurring in the Arbuckle Mountains of Oklahoma, is shown in Figure 10. This fold is in the weak calcareous beds of the Simpson which lie between the heavy Simpson sandstones and the Arbuckle limestone.

To the east of the Lake Erie region at Trenton Falls, New York, intra-formational folds occur in the Trenton limestone at two horizons, the rest of the strata being parallel and not folded. These folds recently have been illustrated and described by W. J. Miller.[1] He says:

> Within the folded zones the layers are, in rare instances, scarcely disturbed; sometimes they are only gently folded; most commonly they are highly twisted or contorted; while occasionally some of the layers are broken, and pushed or faulted over others.

Earlier, L. Vanuxem illustrated and described these folds as follows:

> For thirty or more feet in length, and from three to five feet in thickness, the rock exhibits extraordinary contortions for one whose layers are so regularly disposed, forming almost semicircular curvatures, and not unlike the writhings of a huge serpent. When the contortions are observed, they show a crystallized white limestone, enveloped in the usual calcareous shaly materials, proving that the disturbance was caused by the crystallization of the white limestone forming a layer.[2]

Later, the same folds were described and illustrated by T. G. White.[3]

Folds of this type in western Pennsylvania have been descrbed by R. R. Hice as follows:

> At the site of Dam No. 5 on the Ohio River, on the eastern edge of the Beaver quadrangle between the towns of Rochester and Freedom, a recent railroad cut exposes, in a distance of 600 feet, a series of foldings involving the strata between the base of the Lower Kittanning clay and the horizon of

[1] W. J. Miller, *Jour. Geol.*, XVI (1908), 428–33.

[2] L. Vanuxem, *Geol. of 3d Dist. N.Y.* (1842), p. 53.

[3] T. G. White, *Trans. N.Y. Acad. Sci.* (1895), pp. 71–96, Plate 3A.

the Middle (Upper) Kittanning coal (about 35 feet) in no way involving the underlying strata or those above the horizon of the Middle Kittanning.[1]

W. G. McGee has described some similar small folds and faults in the Cedar Valley (Devonian) limestone of northeastern Iowa.[2] While the folds are within the single formation so far as observed, they are more gentle than intra-formational folds commonly are, and in the illustration given, the deformation is near the surface. The folding is associated with brecciation in the limestone, and as brecciation was coeval with deposition, the deformation and brecciation were thought to have been contemporaneous. The same type of folds occurs in the Quaternary clays along the Black River canal feeder about 3 miles from Boonville, New York, where a series of closely folded layers in a folded zone occurs between unfolded parallel strata on either side.[3] I. C. Russell also describes and illustrates intercalary folds in Quaternary deposits in the Lake Mono region of California, and concludes that they were formed in some manner at the time of deposition.[4] E. M. Kindle explains folded sands and clays between non-folded beds in Nova Scotia and southern Ontario by movement of soft muds beneath, due to irregular weighting.[5]

The only folds of this type found in the Lake Erie region are extremely small and unimportant (Fig. 22). On the northeast side of Twenty Mile Gulf, one-fourth mile west of the Pennsylvania–New York state line, a small fold in the vertical bank is inclosed between horizontal strata above and below. The fold is up about 25 feet in an 80-foot bank. Only about 5 feet of strata are involved. The thickening of the strata above the fold either side of the crest indicates that a few of the beds were slightly deformed soon after their deposition, before the superjacent stratum was deposited, as the latter fills in the depression either side of the crest of the fold. The second and third beds above the fold become uniform in thickness and horizontal in position.

Parallel folds.—Numerous small folds with axes parallel with the trend of valleys occur in the floor of many of the post-glacial valleys of the area. The folds generally are small, involve only a few feet of strata, and usually are limited entirely to the valley floor, affecting the

[1] R. R. Hice, *Bull. Geol. Soc. Amer.*, XXII (1910), 716–17, Abs.

[2] W. G. McGee, *Eleventh Ann. Rept. U.S.G.S.*, Part 1 (1889–90), pp. 337–38.

[3] L. Vanuxem, *Geol. 3d Dist. N.Y.* (1842), pp. 213–15.

[4] I. C. Russell, *8th Ann. Rept. U.S.G.S.*, Part 1 (1886–87), pp. 307–10.

[5] E. M. Kindle, *Bull. Geol. Soc. Amer.*, XXVIII (1917), 323–34.

walls of the valley in only a few instances. This type of fold occurs in many parts of the area, but is especially common in the steep, post-glacial valleys in the vicinity of Meadville, and in the southern tributaries of Walnut Creek, 5 miles southeast of Erie. Figures 23 and 24 represent two of the parallel types of folds from the Meadville region. In Figure 23 the box in the right foreground rests on the crest of the anticline over the joint crack along the axis. The stream crosses the crest and flows diagonally across the valley down the dip on the right

FIG. 22.—Small fold with strata horizontal above and below it in Twenty Mile Gulf ¼ mile west of New York state line.

limb. At the left the beds are dipping into the north bank of the stream. The fold is in sandy beds 2 to 3 inches in thickness in the upper part of the Riceville shale. It is about 30 feet wide and 160 feet long, and is the upper one of a series of four occurring in this ravine. Figure 24 shows the crest of a fold beneath the roots of a tree in the edge of the flood plain. The strata are sandy shales in the upper part of the Riceville formation. The axis is N.50°E., and the dip near the crest is 34°NW. and 30°SE., but the limbs flatten out rapidly. The fold is about 60 feet wide and 260 feet long, and 8 to 10 feet of exposed strata are involved. While folds of this type are more common in the smaller valleys with narrow floors and steep sides, some also are found in the creek bottoms of the larger streams tributary to Lake Erie.

Transverse folds.—The most important folds of the area are those with axes transverse to the valley, so they are exposed in the flood

plains, terraces, and valley walls. The width of the folds varies from a few feet to over 500 feet. The rise of the strata from the side to the

FIG. 23.—Anticline having axis parallel with valley, in Bemistown Run, 2½ miles northwest of Meadville, Pa.

FIG. 24.—Small anticline in the bottom of Park Avenue ravine, at the north edge of Meadville, Pa.

center of the fold is seldom more than 12 feet. Numerous terraces, varying from 10 to 40 feet, and a few as high as 60 or 80 feet, are deformed by the folds. While the axes of a few folds trend about north and south,

and a few others east and west, the majority, about three-fifths, trend in a northwesterly direction, and the remaining ones in a northeasterly direction.

Fig. 25.—Unsymmetrical anticline in 18-foot terrace $\frac{3}{4}$ mile southeast of Girard, Pa.

Fig. 26.—Anticline along Twenty Mile Creek $\frac{1}{4}$ mile south of the N.Y., C. & St. L. R.R., 5 miles east of North East, Pa.

In this area the strata involved are the Upper Devonian and Lower Mississippian. To the east, in central New York, numerous faults and

folds have been recognized in formations extending in age from Cambrian[1] to Devonian.[2] To the northeast, on both sides of Lake Ontario, folds occur in the Queenston shale of either Silurian or Ordovician age. Besides the transverse folds used in other connections in Figures 8, 12, 31, 33, 38, and 41, a few other characteristic ones will be illustrated and described. One of the more open folds, quite unsymmetrical in form, is shown in Figure 25. This asymmetry is clearly indicated by the difference in dip in the two limbs. The dip to the right toward the northeast is 17°, while to the left of the crest it is 37° to the southwest. The fold is in the lower part of the Girard shales, which here contain numerous sandstone beds. While most of the sandstone beds are only 1 or 2 inches thick, the one seen most clearly in the picture has a thickness of 7 inches. The strata rise 14 feet from the sides to the center of the fold, and it has a total width of 300 feet. The axis trends N.80°W., and about one-fourth mile to the northwest it is exposed again where a western tributary of Elk Creek crosses it.

Another transverse fold, much closer than that shown in Figure 25, is illustrated in Figure 26. The axis of this fold is N.25°E., and the dip on the left toward the northwest is 26°, while on the right toward the southeast it is 40°. The closer part of the fold is only 30 feet wide, but the total width is about 300 feet. A very abrupt bend occurs in the strata of the southeast limb, where the highly dipping beds meet those of more gentle dip. This abrupt bend has almost reached the point of rupture. This fold is in the formation called Portage by the earlier writers,[3] but later studies[4] seem to place it in the Chemung. The rocks consist of numerous thin sandstone beds separated by loose dark-gray shales. This is one of the small series of folds in which the axes have a northeast trend. It also is one in which the 14-foot terrace is markedly deformed for a long distance above the crest of the fold.

Another fold of this general type, which, however, is transverse not to a valley but to the direction of the lake shore, is shown in Figure 27. It is in a low cliff along the lake shore 3 miles east of Erie. The axis is N.20°W. It is distinctly unsymmetrical in form, having a northeast dip of 45° and a southwest dip of 14°. The closer part of the fold is 60 feet wide. Thin flaggy sandstones of the Chemung are separated

[1] J. B. Woodworth, *N.Y. State Mus. Bull. 107* (1907), p. 21.

[2] P. F. Schneider, *Amer. Jour. Sci.*, 4th Ser., XX (1905), 310, 311.

[3] I. C. White, *Second Geol. Surv. Pa.*, Rept. Q4 (1881), pp. 119–20; and J. Hall, *Nat. Hist. N.Y. 4th Dist.*, Part 4 (1843), p. 238.

[4] J. M. Clarke, *N.Y. State Mus. Bull. 69* (1902), p. 853.

by thin layers of shale. The loose top of the fold is thrust up into the glacial till.

One of the very small transverse folds is shown in Figure 28. It has a width of about 50 feet, and is of the gentle, open type. It occurs

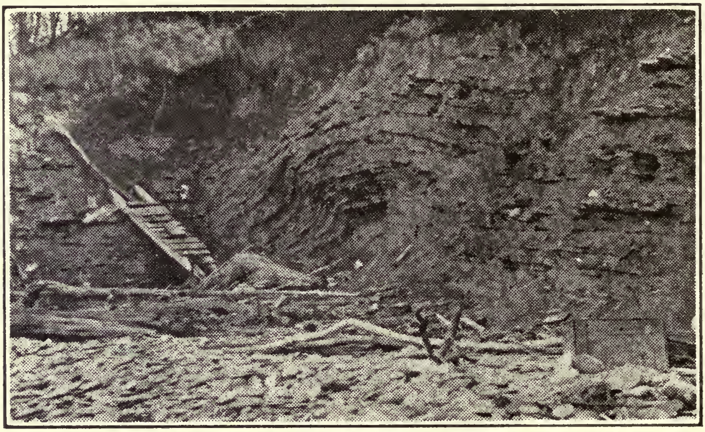


FIG. 27.—Anticlinal fold with uneroded crest, 3 miles east of Erie, Pa.

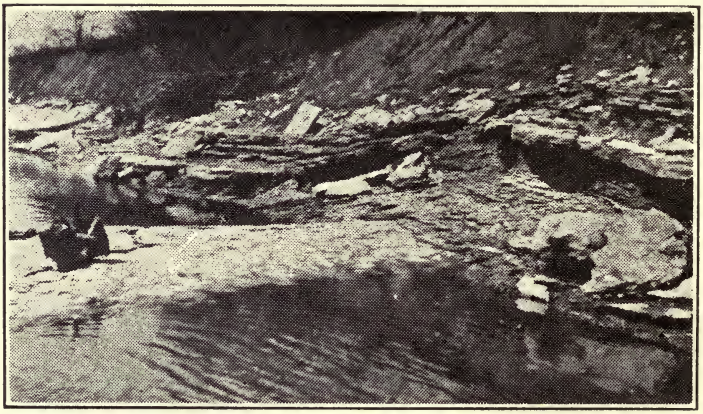


FIG. 28.—Small anticline along Elk Creek $\frac{3}{4}$ mile west of Miles Grove, Pa.

in the flaggy sandstones called Portage, in the east bank of Elk Creek, about three-fourths of a mile west of Miles Grove, Pennsylvania. Thin sandstone beds and sandy shales are interbedded with the thicker beds of sandstone. This small fold with its axis N.30°W. seems but a small

buckle on a much larger anticline to the southeast. The axis of the latter trends N.55°E., so the axes of the smaller and larger folds are about at right angles. Out in the channel to the left of the picture, the heavy sandstone has been completely cut away at the crest, and is seen to be breaking beneath and at the left of the knapsack. This fold illustrates the way in which the loose shales are readily eroded from the crest by the stream, while a heavy sandstone bed may resist the erosive work of the stream for a considerable period of time.

Faults.—Under the heading of local structures it has been noted that the rocks of this area, besides the folds, are affected also by thrust faults. These faults have only a small amount of displacement, varying from a few inches to 7 feet. In the majority of cases the fault planes are low, and the horizontal displacement greatly exceeds the vertical. In many instances the faults are in some way connected with folds, but this is not always the case with some of the smaller ones.

Faults unrelated to folds.—Illustrations of two small thrust faults, in which no relation to folds was discovered, are shown in Figures 29 and 30. In Figure 29 the fault is in the lower part of a 30-foot bank of Girard shales on the east side of Little Elk Creek, $3\frac{1}{2}$ miles southeast of Girard, Pennsylvania. The fault plane here dips northeast about 20°. To the right of the picture it dips more steeply as it goes beneath the floor of the valley. The amount of displacement is thought to be slight, as it is all taken up in the loose shales at the left. A brecciated zone occurs back of the hammer.

The second illustration of a small fault unrelated to a fold is shown in Figure 30. In this fault the plane dips 35° to the southeast. It shows only about 8 feet above the level of Sixteen Mile Creek, along which it occurs 3 miles southeast of North East, Pennsylvania. It seems to have less than a foot of displacement. Above the fault plane the movement has been taken up by the loose shales, there being about 100 feet of them above in the bank.

Faults related to folds.—Many of the thrust faults of the area are definitely related to folds, or are closely associated with them under conditions suggestive of some relation. In connection with the description of the fold in Figure 4, it was noted that the marked asymmetrical anticline was broken at the crest, and that the strata above it were broken and faulted.[1] Figures 31 and 32 show faults below grading into folds above. In Figure 31 the fault is in the middle of the broad, gentle

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, I (1909), 516, Fig. 421; and Bailey Willis, *Thirteenth Ann. Rept. U.S.G.S.*, Part 2 (1891–92), Plate 95.

anticline. The fold is symmetrical, with a dip of 8° in each limb. The direction of the axis is N.60°W. The fold is 140 feet wide and has a rise of 4 feet at the center. The plane of the small fault in the center,

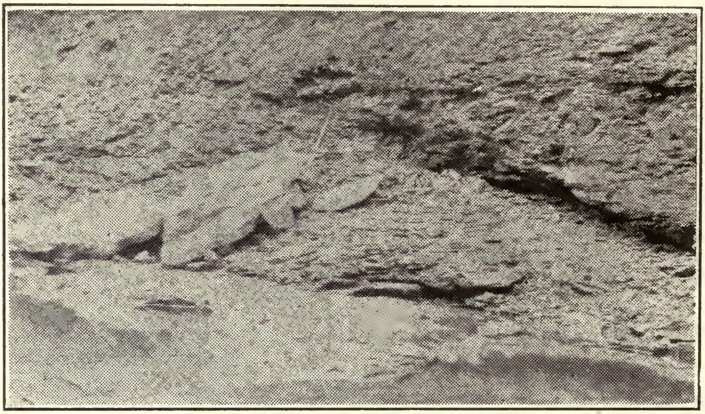


FIG. 29.—Thrust fault in east bank of Little Elk Creek, $3\frac{1}{2}$ miles southeast of Girard, Pa.

FIG. 30.—Small thrust fault in high bank of shale along Sixteen Mile Creek, 3 miles southeast of North East, Pa.

dipping northeast 20°, extends below the valley floor. The displacement in the fault is slight, the throw and heave being nearly equal—the former 10 inches and the latter 9 inches. This fold and fault are in a

terrace at the south edge of the bridge crossing Elk Creek just west of Girard. The terrace is 32 feet high at the bridge and increases to about

FIG. 31.—Small thrust fault in center of a symmetrical anticline, Elk Creek, at west edge of Girard, Pa.

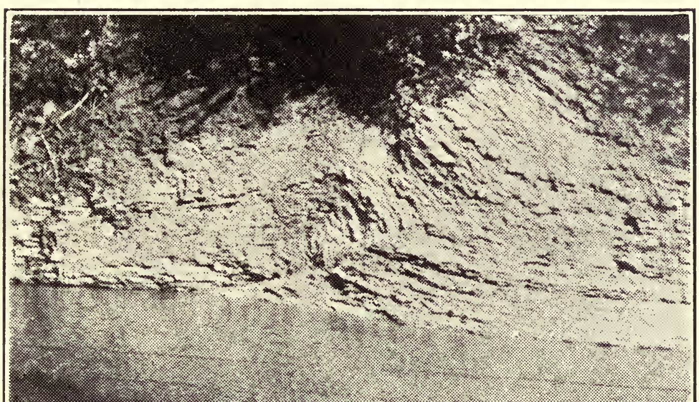


FIG. 32.—Thrust fault below grading into a fold above, Walnut Creek, 1 mile west of Swanville, Pa.

38 feet over the crest of the fold. In Figure 32 the plane of the thrust fault emerges from beneath the water and the fault below grades into an unsymmetrical fold above.[1] In accordance with this condition are

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, I (1909), 516, Fig. 422.

the experiments of Bailey Willis in producing folds and faults by lateral pressure.[1] This fault is in a 20-foot terrace on the west side of Walnut

Fig. 33.—Unsymmetrical fold with two thrust faults, the larger one in the upper sandstone bed and the smaller in the lower bed at the left edge of the picture, Paine Creek, 6 miles east of Painesville, Ohio.

Fig. 34.—Two thrust faults with a small anticline between, the larger fault being at the left of the fold, along a southern tributary of Elk Creek, ¾ mile south of Girard, Pa.

Creek between the two railroads 10 miles southwest of Erie. The fault plane dips 30° south, and the throw is about 2 feet 6 inches.

[1] Bailey Willis, *Thirteenth Ann. Rept. U.S.G.S.*, Part 2 (1891–92), Plates 91, 93.

Other ways in which faults are related to folds are shown in Figures 33 and 34. The illustration in Figure 33 shows a marked unsymmetrical fold and two faults. The fold is 47 feet wide, with a southwest dip of 8° and a northeast dip of 52°. The axis is N.60°W. The upper 11-inch sandy stratum has been faulted at the right of the fold, being thrust 4 feet 6 inches over the horizontal part of the same stratum at the right. At an interval of 3 feet 8 inches below this stratum is a second 16-inch sandstone bed, which because of the fold, is carried beneath the level of the creek at the right. This lower heavy stratum, which is sharply folded toward the right, is overthrust at the left edge of the picture, for a distance of 21 inches, where the fault plane dips 17° toward the northeast. The high part of the bank above the fold is about 40 feet. This fold and the faults are just east of the wagon bridge across Paine Creek, six miles east of Painesville, Ohio, and are in the Chagrin formation.

Still another relation of faults to folds is shown in Figure 34, where two faults occur on either side of a small anticline. This small fold is well down on the west limb of a much larger anticline which seems to be the northwestward continuation of the one shown in Figure 25. The anticline in Figure 34 is in a low terrace consisting of 5 feet of shales and sandstones, two of the beds of sandstone being respectively 4 and 8 inches thick. In the fault at the left of the anticline the throw is 2 feet 3 inches and the heave 4 feet 6 inches, and the fault plane dips 30° southwest. In the smaller fault at the right of the anticline the throw is 5 inches and the heave 8 inches. These folds and faults occur along a southwestern tributary of Elk Creek, one-fourth mile northwest of the exposure of the fold shown in Figure 38. Here the overthrusts are on the west limb and toward the center of the large anticline. In the exposure of the same large fold downstream about 1,200 feet, there is one larger fault with a throw of 6 feet and 6 inches, the trace of the fault plane being N.80°W.

In some instances thrust faults, while not directly associated with folds, occur only a short distance from them, and so are thought to have resulted from the same stresses that formed the folds. This relation of fault and fold exists in the Twenty Mile Gulf one-fourth mile south of the New York, Chicago and St. Louis Railway. A marked unsymmetrical anticline with steeper dip to the southeast occurs in the terrace on both sides of the creek. About 100 feet upstream there is a thrust fault with the trace of a plane parallel with the axis of the fold, N.25°E., and both are parallel with a bank 100 feet high a short distance to the southeast. The fold is shown in Figure 26.

CONSIDERATION OF THE ORIGIN OF FOLDS AND FAULTS

Many and varied causes have been assigned for the origin of folds. A large number have been formed in regions of igneous activity, by the intrusion of large magmatic masses beneath and into sedimentary rocks. Other causes assigned are: heat of igneous rocks, rise in temperature since the glacial period, pressure of natural gas, glacial pressure, drag of glaciers, flexing by ice pressure, drag of icebergs, landslides, pressure developed by alteration of iron sulphides, weathering, compacting of soft sediments, solution, crystallization, differential movements in large faults, pressure of valley walls, relief from pressure, pressure of sediments in a delta, and tangential compression.

Igneous activity.—In the area under consideration the folds are thought to have had no relation to igneous activity, as the nearest igneous rocks known are some dikes at Syracuse, Dewitt, Manheim, and Ithaca, New York,[1] 150 miles to the east. However, in other parts of the country, many folds have resulted from the intrusion of igneous material from beneath into the sedimentary rocks. Numerous examples of folds resulting from these intrusions are found in the Cascade, Sierra Nevada, and Rocky mountains, and many folios of the United States Geological Survey[2] show structure sections in which the folds are due to igneous activity. While folding from this cause generally results from stresses initiated by the injection of large masses of igneous material up through the sedimentary beds, a more indirect cause suggested in a formation adjacent to such material is the expansion of that formation by heat transmitted from igneous rocks above it. A. W. G. Wilson has described some folds in the Keweenawan dolomite at Cook Point in the Nipigon Basin of Canada, which are covered by a sheet of diabase 120 feet thick, the anticlinal arches projecting up into the diabase. Concerning the origin of the folds he says:

> No dikes were found in the dolomite, though they may occur. The folds may have been caused by their intrusion, or as seems more probable in the absence of any evidence that dikes are present, they may have resulted from the expansion of the dolomite when heated by the molten trap.[3]

Inasmuch as no igneous rocks occur in or near the lake region studied, folds cannot be attributed to heat from them.

[1] P. F. Schneider, *Amer. Jour. Sci.*, 4th Ser., III (1897), 458.

[2] Structure Section Sheets, U.S.G.S. Folios: *Phillipsburg, Mont.*, No. 196; *Livingston, Mont.*, No. 1; *Little Belt, Mont.*, No. 56; *Bradshaw Mts., Ariz.*, No. 176; *Santa Cruz, Cal.*, No. 163; *Downieville, Cal.*, No. 37; *Redding, Cal.*, No. 136; *Truckee, Cal.*, No. 39; *Mount. Stuart, Wash.*, No. 106; *Snoqualmie, Wash.*, No. 139.

[3] A. W. G. Wilson, *Geol. Surv. Canada Mem. 1* (1910), pp. 118, 119.

Rise in temperature at close of glacial period.—This cause was suggested by G. K. Gilbert for some of the small folds in the eastern part of the area in western New York. He discovered several small post-glacial anticlines in the horizontal limestones of Jefferson County, New York, and in the shales near Dunkirk, in the western part of the state, and suggests that they may have resulted from expansion caused by the warming up of the surface layers of the rocks as they recovered from the cold of the glacial period.[1] In a paper on "Some New Geologic Wrinkles" (given before the American Association for the Advancement of Science at Buffalo), he says:

> In Jefferson and Chautauqua Counties, New York, there have been observed small anticlinal ridges involving strata otherwise little disturbed. Their relation to glacial deposits and striation show them to be of post-glacial origin, and they are believed to have arisen from the horizontal expansion of superficial strata consequent on post-glacial amelioration of climate.[2]

While water from the glaciers may have cooled the rocks below their normal temperature, it is thought that the rise resulting from the recession of the ice necessary to bring them back to their normal temperature again, would not be sufficient to set up lateral stresses in them. Then, too, a type of folds and faults is common in this region which is not found in other glaciated areas where there was a corresponding rise in temperature after the ice receded.

Pressure due to expansion of ice.—In describing and illustrating some of the folds of western New York, in the eastern part of this area, James Hall suggested the uplifting by ice as a cause for some of them. He notes several along the shore of Lake Erie, and says:

> In other parts of the district these uplifts have produced lines, which, being more easily excavated, have become the channels of streams. Many beds of streams present this appearance, but in most cases I have been inclined to refer the apparent phenomena to the very partial uplifting of the strata by ice.

Very many instances doubtless are due to this latter cause, but there are others which cannot be referred to such an influence. He then gives an illustration of a fold in the south branch of the Cattaraugus Creek, in which the strata beneath the bed and in both walls are involved. He says of the origin of this fold:

> The disturbance here is so great, that it seems due to some more powerful agency than the freezing of the water. Still, however, so many points present

[1] G. K. Gilbert, *Amer. Jour. Sci.*, 3d Ser., XXXII (1886), 324; and *Amer. Assoc. Adv. Sci. Proc.*, XXXV (1886), 227.

[2] G. K. Gilbert, *Proc. Amer. Assoc. Adv. Sci.*, XXXV (1886), 227.

similar appearances, which are evidently due to the latter cause, that it is not easy to decide.[1]

Smallwood and Hopkins have suggested that the presence of running water in most of the valleys would prevent the rocks beneath from freezing.[2] However, the shifting of the stream laterally across the valley floor would expose rocks beneath low flood plains to frost action in the course of this lateral shifting. It is thought that the pressure resulting from ice expansion has not been an important initial cause of deformation of the area. After the rocks have been deformed, and the edges of the strata exposed by erosion, the expansion of ice between beds doubtless does increase the deformation by lifting parts of the strata higher, thus materially increasing their dip. In the central part of some of the folds, numerous joint cracks occur, the strata are loose, and high dips are common. Part of the work of loosening and raising these beds doubtless is due to the expansion of ice between the strata. Note that these conditions are shown well at the crest of the fold illustrated in Figure 24.

Alteration of iron sulphides.—A series of small folds near Cleveland has been described by F. R. Van Horn.[3] He has computed that in the alteration of iron sulphides to iron sulphates and alum-like compounds there would be nearly a threefold increase in volume. He thinks that locally there has been sufficient iron sulphide in the rocks so that the marked increase in volume due to the alteration would cause pressure capable of forming the folds.

At various localities in the area considerable aluminous material in the form of incrustations on the shales is found. Notable deposits occur on the shales involved in the fold and fault shown in Figure 31. However, numerous deposits of this same type have been observed on the shales at various places where no folds have been developed, and furthermore, most of the folds of the area under consideration have no such deposits of aluminous material related to them.

Another point to be considered is the solubility of the iron sulphate. In a moist room, where water is not present in a form to carry away the products of alteration, an incrustation of tiny crystals will form in a few months on the surface of marcasite of a porous, impure variety. Were the alteration to take place in the shale below the surface of the

[1] James Hall, *Geol. 4th Dist. N.Y.*, Part 4 (1843), pp. 293–97.

[2] W. M. Smallwood and T. C. Hopkins, *Bull. Syracuse Univ.*, 4th Ser., No. 1 (1903), pp. 18–24.

F. R. Van Horn, *Bull. Geol. Soc. Amer.*, XXI (1909), 771–73.

ground, a minor part might be precipitated, but the major part would be taken into solution and carried away. If then iron sulphate, because of ready solubility, is largely carried away by ground-water, is it possible that the process of alteration of iron sulphide still may be an important factor in producing stresses capable of deforming rocks? Is there a marked increase in volume in the alteration of the iron sulphides to the hydroxides? C. R. Van Hise speaks of the alteration of the iron sulphides as follows:

The minerals pyrite and marcasite may by oxidation pass directly into (1) hydrated sesquioxide of iron, of which, ordinarily, limonite (not crystallized; sp. gr. 3.80) is the most common kind; (2) magnetite (isometric; sp. gr. 5.174); (3) ferrous sulphate which may be removed in solution; or (4) may be decomposed by further oxidation, either at the place of formation or elsewhere after a longer or shorter time, into hydrated sesquioxide of iron, ordinarily limonite.[1]

In regard to volumetric changes in this alteration he says:

In the change of pyrite to limonite, the volume is increased 2.93 per cent; to magnetite, is decreased 37.48 per cent; in the change from marcasite to limonite the volume is decreased 0.14 per cent.[2]

Thus it is seen by the alteration of the pyrite to limonite the volume is increased less than 3 per cent, and by the alteration of marcasite to limonite there is a real though slight decrease in volume. So it is the form in which iron sulphide occurs that determines whether there be an increase or decrease in volume when alteration takes place. Even when the alteration of pyrite takes place, it is believed that the slight increase in volume would not be effective in producing stresses capable of folding the rocks. This idea is borne out by the fact that a formation like the Huron shale, which contains much more pyrite than the Chagrin formation, has not been deformed by the weathering of pyrite.

Still another factor to be considered is the form of the deformation. It is noteworthy that while small anticlines are described by Van Horn, there is also a monocline, indicating that in one instance the stress resulted in a different type of fold. The folds are post-glacial, as their sharp crests protrude into the glacial deposits above. The very fact that sharp anticlines have been formed indicates that the horizontal component in the stresses has been relatively large. Unless concentrations of iron sulphide were in linear form, deformation due to increase in volume, with vertical stresses predominating, would form domelike

[1] C. R. Van Hise, *U.S. Geol. Surv. Mono. 47* (1904), pp. 214, 215.

[2] C. R. Van Hise, *ibid.*

uplifts instead of anticlines. Furthermore, the disturbance goes deep enough to involve parts of the unweathered shale, thus indicating that the alteration of the materials in the shale is not an important factor in their deformation.

While an important suggestion has been given in calling specific attention to this phase of alteration of iron sulphides, it does not seem probable that this alteration in the shales has been an important factor in their deformation, because numerous folds occur where the content of the iron sulphide is very low, and at other places, where much is present, and the alteration products abundant on the surface, no deformation has occurred. The process is thought to be unimportant, too, because of the solubility of iron sulphate, because the anticlines seem to indicate lateral stresses rather than vertical, and because unweathered parts of the shale are involved in the folds.

Weathering of rocks.—For a large number of very small folds, weathering has been assigned as the cause. Generally they are tiny arches a few feet across and involving only 2 or 3 feet of strata. Such tiny arches are of frequent occurrence in the walls and floors of valleys, and in the sides and bottoms of quarries. In some instances a single bed is arched up, as in the case of the Niagara limestone in the bottom of the Lyons quarry along the Des Plaines River, at the southwestern edge of Chicago.

Several thin beds may be involved, as in the case of a fold illustrated and described by M. R. Campbell, found in the central part of Logan County, Arkansas, 50 miles east of Fort Smith.[1] About two feet of strata show distinct arching, but being sandstones the strata are much broken, while the rocks seem to be affected laterally for only 3 or 4 feet. He considers creep and freezing as possible causes, but thinks expansion due to weathering the most probable one. He speaks of the complexity of the process, noting that it involves both chemical and mechanical changes of a nature to increase the volume. However, he decides that the most important element is the opening of joints and cleavage fissures, and also notes the possible effect of ice and roots in the cracks, but says:

> Although the amount of opening in each joint is small, the aggregate of hundreds of thousands of joints would tend to set up stresses parallel to the bedding, and in course of time these stresses would reach the point of rupture of the beds involved, and a fault or fold would be produced.[2]

In general, joint cracks are evidence of lengthening of a stratum or a contraction of the material in it. If numerous joint cracks are open,

[1] M. R. Campbell, *Jour. Geol.*, XIV (1906), 718–21.

[2] M. R. Campbell, *ibid.*

lateral stresses should be relieved by closing the cracks rather than by arching the strata. In a region in which folds are common, the numerous open joints in one formation, a shale of the Portage group, is assigned by the present writer as a reason why almost no folds were found in it. Of the various processes of weathering, those most effective in producing stresses are expansion, due to rise in temperature and to freezing, and increase in volume by hydration.

In the arching of a single stratum it is believed that solar heat chiefly is responsible, just as sidewalks are buckled and steel rails bent by the excessive heat. Alteration and hydration of some minerals cause them to expand, so it is thought that stresses competent to make the tiny folds might readily result. It is possible that some of the tiny bucklings in ravines in this area may be due to these weathering processes.

Stresses due to crystallization of limestone.—The force of crystallization of limestone is given by L. Vanuxem[1] as the cause of the intraformational folds at Trenton Falls, New York. Speaking of the folds he says:

> When the contortions are examined, they show a crystallized white limestone, enveloped in the usual calcareous shaly materials, proving that the disturbance was caused by the crystallization of the white limestone forming a layer; which, for want of room to expand, this effect being simultaneous with the action as in freezing of water, was forced to recoil, and thus form the contortions noticed. It is not unlikely that the water of the mud from whence the shale was produced, was the solvent of the calcareous particles, enabling them to assume the crystalline state. At one of the extremities of the contorted rock, where it joins the undisturbed portion, it is broken into fragments, some of which are turned on end by the violence of the action.

Without doubt there is a power in crystallization which originates stresses in the rocks. A familiar example of this force is seen in the ability of ground ice not only to overcome the force of gravity in its growth, but also to raise a considerable amount of soil, stones, and vegetable matter with it. Though differing quantitatively, this force of crystallization is well illustrated in the formation of crystals, often of large size, of such minerals as staurolite and garnet. Though formed under great pressure, these minerals in their growth have the power to force the materials about them away to make room for their enlargement.

But though the force of crystallization be recognized as capable of setting up some local stresses in the rocks, there is a question of its application to the phenomenon of folding. W. J. Miller, after a careful

[1] L. Vanuxem, *Geol. of 3d Dist. N.Y.* (1842), p. 53.

examination and comparison of the rocks at Trenton Falls in the folded zone with those on both sides of it, says: "No difference in crystallization can be detected."[1] There seems no reason for the development of marked lateral stresses in the bed of limestone, when there is ample opportunity for vertical expansion in the shales above and below it. Furthermore, no instance is known in which the crystallization of any rocks seems to have developed stresses competent to deform them, unless it be those around the salt and gypsum domes of the Gulf Coastal Plain, and even here it may have been of far less importance than the increase in volume resulting from the change of limestone to gypsum.[2]

Deformation by solution beneath.—There are two types of conditions under which deformation has been attributed to solution—the formation of sinks and channels by the solution of limestone, and the solution of an underlying stratum of salt or gypsum. The first type is illustrated in Miller County, Missouri, southeast of the center of the state, where two Cambro-Ordovician limestones, the Gasconade and the St. Elizabeth, have been affected. In this area it is said of the St. Elizabeth formation:

> This formation is complexly flexured very much the same as the Gasconade underneath. Steeply dipping beds are more common in this formation than in any other. Many of them have resulted from the falling in of the roofs of caverns due to underground solution.[3]
>
> A very large number of minor dislocations in western Kentucky doubtless are also due to the sinking of extensive caverns.[4]

Deformation from the same cause has taken place in the southwestern lead and zinc area, where enlargement of old solution cavities in comparatively recent time has let the superjacent Cherokee shales down and deformed them.[5] There also is a more indirect way in which solution has been related to the deformation of the Cherokee shales. After the latter formation was deposited in the solution depressions in the limestone, the area was subjected to compression in post-Carboniferous times,[6] and the shales, being less competent than the limestones, have been buckled up by this compression.[7] In these instances of deforma-

[1] W. J. Miller, *Jour. Geol.*, XVI (1908), 430.

[2] W. Kennedy, *Bull. S.W. Assoc. Petroleum Geologists*, I (1917), 58, 59.

[3] S. H. Ball and A. F. Smith, *Geol. Miller Co., Mo., Bur. Geol. and Min.* (3a), I (1903), p. 58.

[4] N. S. Shaler, *Geol. Surv. Ky.*, New Ser., III (1877), 231 (bottom paging).

[5] Observation of writer at Commerce, near Miami, Okla.

[6] C. E. Siebenthal, *Econ. Geol.*, I (1906), 128.

[7] *Joplin Folio*, No. 128 (1907), p. 9.

tion of limestones and shales as a result of solution, several areas were affected, each entirely unrelated to the others unless two solution cavities were near together, and even then general tangential stresses did not result. Small folds and faults possibly may be a minor part of major movements down into solution cavities.

The second type of conditions under which deformation has been attributed to solution—that of the solution of salt underneath—is a cause assigned for the folding and faulting of overlying limestones in central New York. Wheelock attributes a series of faults in the Scalaris and Helderberg limestones to the solution of salt in the Salina formation beneath them. His explanation is as follows:

> As the rocks of central New York dip slightly toward the south, the hypothenuse of the triangle would be shortened by the dropping down of the overlying formation due to the solution of the salt, and thus produce a lateral pressure in the rocks capable of causing overthrusts.[1]

In a summary of the thrust faults of central New York, P. F. Schneider says:

> Inasmuch as most of the above mentioned disturbances occur in or near the Helderberg escarpment, composed in the main of heavy limestones aggregating several hundred feet in thickness, and the persistence of the faults across central New York, it would seem that all are the result of some considerable force capable of affecting this entire region. In a general way the solution of salt from the Salina formation which immediately underlies the Helderberg series has been regarded as an explanation for all the disturbance of this region.[2]

Though suggesting other possible causes for the deformation, he repeats Wheelock's idea,

> that from solution any settling of the layers must shorten the length of the hypothenuse of the triangle, and thus produce the force which crumpled and fractured the rocks.

Of the faults mentioned by Wheelock, occurring in central New York from Little Falls to Ithaca, those in the northeastern part of the area mentioned need not be considered as resulting from solution of the Salina, as they are in the older formations, the Salina having been eroded back far to the southwest. As to the shortening of the hypothenuse on the monocline by solution of the salt beneath, it may not be irrelevant to inquire whether shortening of sufficient amount would take place to produce any such deformation as is recorded in the central

[1] C. E. Wheelock, *Science*, New Ser., XXII (1905), 673.

[2] P. F. Schneider, *Amer. Jour. Sci.*, 4th Ser., XX (1905), 308–12.

New York area. P. F. Schneider[1] has listed a number of these faults, giving the amount of displacement for them as 15, 3, 3, 2, 4, 42, and 6 feet, or a total for those described of 75 feet.

In regard to the shortening of the hypothenuse as a cause for deformation, it may be noted that most of the faulting and folding is back about 13 miles south of the exposure of the top of the Salina formation. The general southward dip in Onondaga County is given as 40 feet per mile.[2] However, if one figures the fall of the Salina from its outcrop at 400 feet A.T. north of Syracuse, to the Solway Company Well No. 30 near Tully, there is a drop of 741 feet in 25 miles, or a trifle less than 30 feet per mile.[3] Using the larger figure of 40 feet per mile for 13 miles, the distance from the outcrop to the region of the deformation, there would be a fall of 520 feet. Solution for the hypothenuse shows it is less than 2 feet longer than the bottom leg. It is seen then that if there were sufficient solution to drop the hypothenuse the entire 520 feet, there would be shortening of less than 2 feet to account for the deformation noted above. This is entirely inadequate. Furthermore, the thickness of soluble beds is not sufficient to allow a settling to the extent of 520 feet.

The thickness given by Luther for the salt beds of the region is variable, being 180, 214, 220, and 318 feet at different places.[4] If to the largest figure, 318 feet, we add the thickness of the gypsum-bearing shales, 115 feet, there is still less than the length of the opposite leg of the triangle noted above. This would still further reduce the amount of thrust faulting possible from this cause.

It is indicated then that if the salt and gypsum, equal in amount to that now found 13 miles south of the outcrop of the Salina formation, had dissolved from beneath the overlying formations, the shortening of the hypothenuse for the area would have been far too slight to account for the deformation which has taken place. The fact that older formations in the northeastern part of the area have been affected is suggestive that where those older formations go beneath the Salina they may there also be affected, indicating that the faults and folds of central New York, like those farther northeast, represent deep-seated movements of a real tectonic character.

[1] P. F. Schneider, *Amer. Jour. Sci.*, 4th Ser., XX (1905), 308–12.

[2] D. D. Luther, "Geol. Onondaga Co.," *N.Y. State Geol. Rept.* (1895), p. 272.

[3] D. D. Luther, *ibid.*, pp. 255, 256.

[4] D. D. Luther, *ibid.*

Still another point to be considered is the nature of the movement that would take place as a result of solution in a lower one of a series of beds on a gently dipping monocline. If solution is most rapid at and just below the outcrop of the soluble formation, as solution takes place, a slow settling of the edge of the next higher formation would result. As solution increased at points farther down the dip, the settling of the formation above would be correspondingly shifted down the dip. Now if there be a lateral shortening of only 1 or 2 feet in a distance of from 10 to 15 miles, this movement is more likely to be taken up between the beds and in the weak intermediate formations than to break with marked thrusts across the heavy bedded limestones, or throw them into distinct folds.

It is believed that in the area under consideration, to the west of the central New York region, the folds and faults are not due to solution of salt and gypsum. In fact, the deep well at Erie shows no rock salt, but some gypsum mixed with marl at a depth of from 1,700 to 1,815 feet.[1] Thus the absence of salt, and the slight amount of deformation possible as a result of the solution of beds beneath, point to something other than solution as a cause for the folds and faults.[2]

Faulting due to compacting of soft rocks.—It would seem that the conditions favoring the accumulation of tangential stresses of sufficient intensity to fold or overthrust rocks would be present, because of the compacting of softer sediments, only when highly compressible sediments for a region were overlain by well-compacted and more rigid rocks. If compacting over a large area should result in extensive shrinkage of an underlying formation, the settling of the superjacent formations would result in radial shortening. Any considerable radial shortening for a large area would initiate lateral stresses competent to fold and fault the rocks. If, however, the shrinkage is irregular, and limited to small areas, the question of adequacy arises. The arc of the circle is so large and flat that a slight amount of shrinkage over a small area would not have much effect in producing lateral stresses. G. S. Rogers[3] has given this compacting as a possible cause for a small fault which he has found in a coal bed in southeastern Montana, not far from the confluence of the Big Horn and Yellowstone rivers. It is in the

[1] C. S. Prosser, *Geol. Surv. Ohio Bull. 15*, 4th Ser. (1912), p. 414.

[2] More recent experience of the writer in the region of gypsum-bearing rocks of southwestern Kansas has shown that folds and faults due to solution of gypsum differ greatly in character from those in the Great Lakes region.

[3] G. S. Rogers, *Jour. Geol.*, XXI (1913), 534–36.

midst of generally flat-lying strata about 70 miles from the Big Horn Mountains. The thrust is slight, with a displacement of only 29 inches. The form of the fault is peculiar in that the upthrown side is vertical for a distance of about 2 feet, and then is turned in a horizontal position at the top, or practically at right angles to the lower part of the upthrust, as though two forces differing in direction had affected it successively.

Both the character and the competency of the overlying beds would have some influence in determining the manner in which superjacent beds would be affected by local compacting and shrinkage of the underlying strata. H. F. Bain[1] considers the irregular shrinkage in the "oil rock" at the base of the Galena dolomite as the cause of the flats and pitches in the lower part of that formation; the idea being that considerable local shrinkage gave opportunity for the opening of spaces between the beds, and caused diagonal breaks across them analogous to the openings found in a brick or stone wall when a window or door frame gives beneath the masonry above. But in this case no folds or faults resulted in the rocks superjacent to those which were compressed. The compacting of beds by weight of overlying strata doubtless is widespread, and when the superjacent beds are rigid because of crystallinity or other cause, movements necessary to accommodate them to the new positions they may take as a result of shrinkage, cannot be accomplished without considerable lateral movement. Accordingly, lateral stresses will be set up, for the result will be that of radial shortening. If there be real radial shortening, there will be cause for tangential thrust in the ratio of about 1 to 6 for the entire earth,[2] or for an approximate circumference of 24,000 miles. So for the entire earth, 100 feet of radial shortening would give 600 feet of thrust. For a 10-mile arc 100 feet of radial shortening would give $\frac{1}{2400}$ of 600 or $\frac{1}{4}$ foot, and for a 2-mile arc, 100 feet of radial shortening would give $\frac{1}{20}$ of a foot. Two folds with associated faults along Paine Creek have the crustal shortening of 7 feet 8 inches within 2 miles. The ratio for the thrust here because of the shortening would be $1:\frac{1}{2000}$, or to get a shortening of one foot there would be 2,000 feet of depression. But possibly these deformations relieved stresses for a mile either side of the folds, so we should consider the distance for the shortening for 4 miles instead of two. Even for 4 miles there would need to be a depression of 1,000 feet to cause 1 foot of thrust. Along Elk Creek, south of Girard, over 11 feet of shortening has occurred within a mile. The 7 faults farther east in

[1] H. F. Bain, *U.S. Geol. Surv. Bull. 294* (1906), p. 44.

[2] T. C. Chamberlin and R. D. Salisbury, *Geology*, I (1905), 580.

central New York, as noted above, have a total displacement of 75 feet, and these occur within an arc of 10 miles. The displacements in the eastern area should not be added, for they occur in four different localities, Marcellus, East Onondaga, Jamesville, and Manlius, almost in an east-and-west line. As the shortening is a north-and-south one, they probably represent a continued deformation. But a single displacement at East Onondaga is 42 feet, one at Jamesville 15 feet, and four others 12 feet. If depression here has taken place over an arc 10 miles across, the ratio would be $1:\frac{1}{400}$, or there would be a settling of 400 feet to 1 foot of thrust. So to get 42 feet of thrust a depression of 16,800 feet would be required. Also, the shortening noted above does not include several folds that occur in the general region with the faults. Thus from a quantitative standpoint the shortening of the arc of a segment due to settling from compacting of subjacent rocks, is far too small to cause thrusts of even the small magnitude of those in the Lake Erie region or in central New York.

Vertical pressure of valley walls.—W. O. Crosby[1] is credited with having suggested the weight of the overlying strata as an explanation for the marked small folds at Trenton Falls, New York, but W. J. Miller concludes that the overturned folds cannot be accounted for in this way. Smallwood and Hopkins, in their discussion of the origin of the folds near Meadville, consider the possibility of the weight of the valley walls being sufficient to deform the rocks in the bottoms of the valleys, but conclude that they are not sufficiently high to develop an adequate force.[2] This conclusion seems well founded, for the walls of the deepest sharp post-glacial valleys in the vicinity of Meadville reach scarcely 100 feet in height. Sandy shales and some sandstones, as well as the argillaceous shales, are involved in the folds there. The deepest valley on the southern border of Lake Erie, near Westfield, New York, is 400 feet deep. Figuring 165 pounds per cubic foot for the shales and sandstones in the walls of these valleys, there would be only about 460 pounds pressure per square inch on the rocks at the bottom of the valleys beneath the walls 400 feet high, and 115 pounds on those with walls of 100 feet. The crushing strength of the weaker sandstones can hardly be lower than 1,500 pounds per square inch.[3] This is far above either

[1] W. O. Crosby, *Jour. Geol.*, XVI (1908), 430; and *Man. N.Y. Acad. Sci.*, XV (1895–96), 90.

[2] Smallwood and Hopkins, *Bull. Syracuse Univ.*, 4th Ser., No. 1 (1903), pp. 18–24.

[3] L. V. Pirsson, *Rocks and Rock Minerals* (1915), p. 324.

figure for the pressure due to the weight of rocks in the walls of the valleys. It is significant, too, that most of the smaller folds of the area, occurring in the floors of valleys parallel to the walls, are found in those with relatively low walls of about 100 feet or less.

G. F. Becker has given an excellent summary of the rupturing effect of stress due to gravity as follows:

> When gravity acts on a mass, homogeneous strain is, strictly speaking, impossible, excepting within infinitesimal limits of space, each level surface being subjected to greater pressure than the next above it. On the other hand, the forces involved in the deformation and fracture of rocks are very great, except in some extreme instances, such as that of moist clay. For ordinary firm rocks the ultimate strength is such that a column of from one to several thousand feet in height would be needful to produce at its base a pressure sufficient to produce rupture. Consequently in masses of such material from a few score of feet to a few hundred feet in thickness, gravity plays but a small part compared with the rupturing stress.[1]

His conclusions are in conformity with the figures above, showing that the weight of these valley walls is far below that necessary to rupture solid rocks.

Folds due to relief from compression.—Folds occurring in the quarries or valleys frequently are attributed to relief of pressure by the removal of rock from above. Such an explanation has been given for a small anticline in the Queenston shale at the head of Hopkins Creek estuary, south of Lake Ontario, of which it is said: "It probably is a secondary result of erosion, the removal of the overlying rocks permitting relief from compression."[2] But relief from vertical compression alone could have nothing to do with the formation of folds. If marked stresses already exist in the rocks, and the superficial strata by their strength and weight prevent folding, then their removal might permit the stresses resident in the subjacent weaker rocks to become effective by throwing those weaker rocks into folds.

Folds due to weight of delta.—In several places in the western part of the United States, folds occur at the base of large deltas. I. C. Russell has described and figured folds which occur at the base of the Provo delta, along the Logan River, Utah. He suggests as an explanation of the folds, that the weight of 300 feet of delta material pressed out some of the soft, freshly deposited sediments and arched them up into a series of folds, developing the folds of the series successively as it was built

[1] G. F. Becker, *Bull. Geol. Soc. Amer.*, IV (1893), 49–50.

[2] *Niagara Folio*, No. 190 (1913), p. 15.

forward. He computes the difference between weight of water and weight of delta as 75 pounds per square inch.[1] Russell thinks the folds in the lower part of deltas in Lake Lahontan, Utah, and in the Mono Valley, California, also are due to the weight of deltas.[2]

The deformation of soft, unindurated sediments by the weight of a thick delta deposit seems very possible, but a similar weight would have little effect on indurated shales and sandstones such as are folded and faulted in the Lake Erie region. Besides, no deltas of the type and magnitude described by Russell are found in this area.

Deformation due to landslides.—Numerous small anticlines occur in the bottom of post-glacial valleys in the vicinity of Meadville and in the tributaries of Walnut Creek, south of Erie. The valleys are narrow at the bottom and have steep sides. Generally the folds are about parallel with the trend of the valley. Some of these folds are associated with landslides, and W. M. Smallwood and T. C. Hopkins attribute the formation of the folds largely, if not entirely, to this cause.[3] However, many of the folds are in no way related to landslides, and numerous large landslides have caused no deformation of the strata. As the height of the valley walls is generally less than 100 feet, the force from the slow settling of a comparatively small landslide down a 45° slope, is thought to be entirely inadequate to deform 8 to 20 feet of well-indurated shales and sandstones commonly involved in the folds in the valley floors. R. T. Chamberlin[4] has noted much larger folds of this type in materials of the slides along Lakes Zug and Zürich in Switzerland, where the rocks beneath the slide were undisturbed.

A few of these folds, particularly some in the sharp southern tributaries of Walnut Creek, before referred to, not only are related to landslides, but clearly are a part of them. In at least two instances the landslides were forced across the narrow floor of the valleys, and the strata in the lower part of the slide were buckled into anticlinal form by the weight of the upper part of the slide. It would, however, take far less force to buckle up in the end of a slide the strata which have been loosened by the movement, than would be required to deform the undisturbed bedrock of the valley floor.

Should there be a prominent joint in the rock a short distance back in the valley wall about parallel with the trend of the valley, cutting

[1] Credited to I. C. Russell by G. K. Gilbert, *U.S.G.S. Mono.*, I (1890), 162.

[2] I. C. Russell, *Eighth Ann. Rept. U.S.G.S.*, Part 1 (1886–87), p. 310.

[3] Smallwood and Hopkins, *Bull. Syracuse Univ.*, 4th Ser., No. 1 (1903), pp. 18–24.

[4] Unpublished correspondence.

beneath the edge of the valley floor and sloping steeply in the wall, it might determine the plane of a break in the wall. Should a large mass of rock with broad top rest on a relatively small base, the pressure on that base would be greatly increased, and might cause the surface layers of a weak rock to buckle in the bottom of the valley in front of it. It may be well to inquire, in this connection, whether it is possible for folding in a valley floor to initiate landslides. If, because of lateral stresses, the rocks fold up in the valley floor, there might be a slight giving under the edge of the valley in a way to loosen the strata above and cause a landslide.

The illustration of a fold at the base of a cliff antedating a slide is given by F. R. Van Horn.[1] It is in the quarry of the Cleveland Brick and Clay Company, along Mill Creek, at Cleveland. Back a distance from the edge at the top of the quarry wall, which is 112 feet high, a fissure opened August 17, 1908. The following day a small anticline 200 feet long, started to buckle up at the base of the bank, in the shales weakened by the blasting. The day following the initiation of the buckling, the mass of rock, estimated to weigh 87,732 tons, started to settle. It was stated definitely by the quarryman, who watched the phenomena, that the buckling preceded any settling of the mass. After the settling began, it continued at the slow rate of 6 feet in two weeks, and of 20 feet in a little over four months. After the excavation of most of the shale of the slide, it appeared that a joint crack had reached up 80 feet of the 112 in the quarry wall, this crack having determined the location of the fissure at the top of the bank. If this joint crack extended a short distance below the floor of the quarry, the identical conditions exist which are postulated with reference to the valley wall in a landslide described above. In this instance the slide and the small fold parallel with its front seem definitely related. The amount of weakening by the shattering of the shales in the base of the high bank and on the quarry floor is not known, but it may have been very considerable.

Another consideration to be noted in connection with folds related to landslides, both in this quarry and in the valleys in the area studied, is that lateral stresses of importance may already exist in the rocks. If such stresses do exist, and to them are added the relatively smaller ones initiated by the landslides, the combined stresses are then sufficient to overcome the strength of the rocks and bow them up. In this case, while definite stresses are added by action of the landslide, their minor force may be looked upon as a trigger which has added its slight

[1] F. R. Van Horn, *Bull. Geol. Soc. Amer.*, XX (1908), 625–32.

power to the larger forces it sets in motion. Reasons for thinking that such lateral stresses exist in the rocks of the area studied will be given later.

Pressure of natural gas.—In this area gas occurs under low pressure at an average depth of 600 feet. At one locality it is constantly escaping from the crest of the anticline shown in Figure 38. I. C. White[1] has attributed the "minute cracked anticlines" of the area to the pressure of natural gas. However, the wells produce little gas, and that little under low pressure. Furthermore, the folds occur both within and without the areas productive of gas. While the pressure of natural gas clearly produces stresses, it is thought that they are far too weak, with the low pressures common here, to deform the rocks. Besides, the release of strains due to gas pressure doubtless would come in the formation of domes and symmetrical folds rather than in the markedly unsymmetrical ones common in the area under consideration.

Differential movements.—W. J. Miller[2] has suggested that differential movement in the mass of the Trenton limestone, in the large fault at Prospect Village near Trenton Falls, New York, has caused the folds in two horizons which lie between unfolded strata. The suggestion is excellent, and it seems probable that as the end of the upthrown part of the fault has been greatly eroded, these small folds are the best existing index of the amount and character of the lateral movement in the fault. In several instances in the area studied only a few feet of the superficial rocks seem to be involved in the folds. In these few cases the beds underneath are undisturbed, while the more superficial ones are deformed, thus seeming to indicate either more acute stresses or greater weakness in the upper than in the lower rocks. But these very superficial folds seem to be in no way related to a larger fault. In many of the folds, however, the deformation appears to involve the rocks to a considerable depth as well as the superficial ones, but none are related to a large fault.

Glaciation.—Many folds of varying types and magnitude have been attributed to the action of glaciers. Glaciation has been so much abused in having unreasonable destructive and deformative acts attributed to it, that the prevailing tendency now is to scrutinize with care the charge "due to glaciation." The real deformation of rock which may rightly be attributed to glacial action is now thought to be very moderate. The work attributed to glaciation by J. A. Udden[3] and F. W. Sardeson[4]

[1] I. C. White, *Second Geol. Surv. Pa.*, Rept. Q4 (1881), p. 120.

[2] W. J. Miller, *Jour. Geol.*, XVI (1908), 428–33.

[3] J. A. Udden, *Ill. Geol. Surv. Bull. 8* (1908), pp. 255–67.

[4] F. W. Sardeson, *Jour. Geol.*, XIII (1903), 351–57.

seems excessive. Udden describes and illustrates many small folds and faults in the walls of valleys and in coal mines, some of the faults having a displacement of 30 to 100 feet. He thinks the folds and faults near Peoria, Illinois,

> are disturbances in the upper part of the soft bed rock, caused by the pressure and motion of a continental ice sheet in the Pleistocene period; that they are planes marking the outline of immense blocks of large tracts of the uppermost coal measure strata covering probably hundreds of acres of land which have been dislodged from their position, displaced, fractured, rotated horizontally and at times vertically, and partly ground to till.[1]

Sardeson speaks of glaciers "plowing up bed rock,"[2] and transmitting stresses through beds of gravel and till 16 to 20 feet in thickness, over which they are moving with such efficiency as to fold and overthrust the Galena limestone beneath the gravel and drift.

E. M. Kindle and F. B. Taylor[3] have described and illustrated an anticline at Thirty Mile Point, along the southern shore of Lake Ontario just east of the Niagara quadrangle, and they attribute the origin to the pressure of glacial ice, in spite of the fact that it is overturned into the glacial till and includes till definitely beneath the overturned top of the fold. In G. K. Gilbert's[4] earlier description of this fold he advances two hypotheses for its origin, but does not conclude definitely as to either one. If due to glaciation his idea is that the waning ice stopped just north of this, then moved forward again enough to form the fold and overturn it into the drift. The shore has undoubtedly been eroded back a long distance in the sandy shale at this locality, possibly a mile or more. If the glacier moved forward several times over the area, it seems strange that it should wait until a last slight advance to deform the rocks.

J. Le Conte attributes folds in several horizons in clays along Rush Creek, in the Mono Valley, California, to glaciers or icebergs,[5] but I. C. Russell determined that the glaciers did not come within 3 miles of the area described, and that the folds were so widespread, and many of them of such a nature, that they could not have been formed by icebergs.[6]

[1] J. A. Udden, *op. cit.*, p. 265.

[2] F. W. Sardeson, *op. cit.*, p. 356.

[3] Kindle and Taylor, *Niagara Folio* (1913), p. 15, and Plate 19.

[4] G. K. Gilbert, *Bull. Geol. Soc. Amer.*, X (1898), 131.

[5] J. Le Conte, *Amer. Jour. Sci.*, 3d Ser., XVIII (1897), 40.

[6] I. C. Russell, *Eighth Ann. Rept. U.S.G.S.*, Part 1 (1889), p. 309.

There are but two localities in the area studied in which folds of such a character were found that their origin could be attributed to glacial pressure. One was in an open-pit coal mine 5 miles south of Conneautville, Pennsylvania, and the other in shales along Canadaway Creek $1\frac{1}{2}$ miles west of Dunkirk, New York. In both instances the topographic situation, presenting a steep slope toward the north, the general direction from which the ice came, favored the transmission of stress into the coal in one case and the shale in the other, as the ice advanced against these transverse barriers. In both instances the folds are small, only a few feet of strata being involved, and the rocks much broken, indicating that the folding took place without much pressure from above. The two small folds in the coal are shown in Figure 35, and being indistinct they are outlined by the dotted line. The hammer is $11\frac{3}{4}$ inches long. About 6 feet of broken and crushed coal lie above the folds, and a few feet to the right of them, toward the north, the glacial till is intermingled with the broken coal. The coal at the top of the hill is an outlier of a more extensive formation to the south. Apparently the ice, advancing against the steep northern slope of the hill, shattered and slightly deformed the northern end of the coal vein before it was deflected above the top of the hill. The folds in the Dunkirk shale of the Portage group, near Dunkirk, are shown in Figure 36. Three small anticlines occur in the series, and each is about 10 feet wide. The sandstones beneath the shales are undisturbed. The thickness of the shale is 5 feet, and it is overlain by 3 feet of glacial drift and soil. A short distance to the north of the folds the shale presents an abrupt slope to the north.

Because of the topographic situation with reference to the advancing ice front these very small folds in coal and shale seem readily attributable to the pressure of glacial ice. The fact that larger folds due to glacial pressure were not found in this area does not constitute proof that they do not occur elsewhere. It is thought, however, that this extremely minor type of folding is all that can be expected from the glacial ice pressure, because of its softness, and plastic adjustment under compression.

A detailed study of the major and minor deflections of the ice due to various types of barriers would be instructive in this connection, but it cannot be followed here. Brief attention is called to the plastic adjustment of the ice under pressure as indicated by the manner in which it fitted into the irregularities of the rock surface. An illustration of this adjustment is seen in the south quarry at Stony Island, in Chicago,

where the underside of a small projecting ledge of the Niagara limestone has been polished by the wear of the ice and its tools. In another

FIG. 35.—Two small folds in the north edge of an open coal mine. The hammer is $11\frac{3}{4}$ inches long. Five miles south of Conneaut Lake, Pa.

FIG. 36.—Small folds in 5 feet of Dunkirk shales $1\frac{1}{2}$ miles west of Dunkirk, N.Y. The thick homogeneous beds are outlined by the dotted lines.

locality, on Kelly's Island, in the western part of Lake Erie, the ice was forced with great pressure through the sinuosities of a tortuous channel without breaking off the interlocking spurs of the rock.[1]

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, III (1906), 349, Fig. 485.

Drag of icebergs.—In a few instances folds in unconsolidated clays and sands have been attributed to the drag of icebergs over them. J. Le Conte[1] has suggested that explanation for the folds in the clays and sands in the beds deposited in Lake Mono. A like cause has been credited by R. D. Salisbury and W. W. Atwood[2] with the deformation of layers of sand and silt in the glacial lake deposit in the Baraboo region of Wisconsin. I. C. Russell[3] questions the possibility of any type of ice origin for the folds in the former case, but it seems quite possible that local, narrow, irregular areas of unconsolidated sediments might be so deformed. If the grounding and drag of icebergs have caused the deformation of lake beds, the general direction of the current from the ice front to the outlet of the lake would indicate the course of the icebergs, and the axes of the folds would be about normal to the direction of their course.

Tangential compression.—The closed folds and thrust faults of the Taconic, Appalachian, Ouachita, Arbuckle, and Wichita mountains give evidence that stresses of great potency of a tangential nature have been developed at various periods of the earth's history. It is not the purpose here to seek the ultimate origin of these lateral stresses, but simply to suggest the possibility of their presence as a cause for the deformation of the region under consideration. And it is thought that most of the folds and faults are due to widespread lateral stresses, which have been directed in such a way as to cause these minor movements.

Summary of origin of folds and faults.—Of the various causes to which the formation of folds and faults have been attributed, a number of them seem to have no application to the deformation of rocks in the area under consideration; namely: igneous activity, expansion due to heat from adjacent igneous rocks, increase in temperature at the close of the glacial period, crystallization, solution of underlying formations, alteration of iron sulphides, weight of delta, gas pressure, differential movement of beds in a large fault, and drag of icebergs. Three others—pressure of valley walls, release of pressure by erosion, and landslides—have been shown wholly inadequate to develop stresses sufficient to deform any considerable thickness of strata in place. If they have had any effect, it has been by the addition of their relatively slight force to the much greater stresses already in the rocks.

Expansion due to heat, freezing of water, and hydration of minerals, may have helped to form some of the smaller folds, but it is believed

[1] J. Le Conte, *Amer. Jour. Sci.*, 3d Ser., XVIII (1879), 40.

[2] Salisbury and Atwood, *Jour. Geol.*, V (1897), 143.

[3] I. C. Russell, *op. cit.*, p. 309.

that these agents, in the main, have been secondary, increasing dips started by other forces rather than initiating them. In two instances very small folds involving only 5 feet or less of strata, are thought to be due to the pressure of glacial ice, which because of their topographic form and situation, presented very abrupt barriers to the front of the ice. All of the larger and intermediate folds, and many of the smaller ones, are thought to be due to widespread tangential stresses in the rocks, the origin of which will be considered later.

AGE OF THE FOLDS AND FAULTS

The age of the folds and faults will be considered under three heads —pre-glacial, glacial, and post-glacial. An attempt also will be made to determine still more explicitly the age of some of the post-glacial deformations by their relation to a series of terraces.

Pre-glacial.—A number of the larger open gentle folds are considered pre-glacial, the low fold shown in Figure 12 being one of the smaller ones belonging to this group. A number of others were found, but no good pictures were secured. Still more marked folds of this age and type occur farther west in Ohio, outside this area. If an attempt were made to fix the age more closely we can say they are post-Lower Mississippian and pre-Pleistocene. Both Upper Devonian and Lower Mississippian rocks were involved in the deformations, and there was no break in the sedimentation between the Devonian and the Mississippian periods. Possibly some of the folds were formed toward the close of the Mississippian or at the beginning of the Pennsylvanian period, as there is a general unconformity between the rocks of these two systems. Or they may be referable to the Permian, a series of small, gentle folds being formed here when the larger and more intense ones were developed in the Appalachians to the southeast, though they seem rather far removed to be genetically related to the latter. Or there is a possibility they may have been formed still later, between the Permian and Pleistocene.

Glacial.—As has been noted above in connection with the origin of folds, a few small ones are thought to be due to the pressure of glacial ice, and accordingly are of Pleistocene age. They are considered to belong to the early part of this period, being formed when the advancing ice first was opposed by rather abrupt barriers. Soon after the first impact of the front of the glacier with the barriers, the ice doubtless was deflected above them. It then began to erode the crest of the escarpments and to deposit till at its base, thus developing an easy

gradient over which to move. The folds of this age that were observed are in the surface coal mine (Fig. 35) and in the shales near Dunkirk (Fig. 36).

It is possible also that some of the folds and faults, though not attributable to glacial forces, may have been developed during the Pleistocene period, but distinctive evidence marking them of glacial age is wanting. The sharply overturned anticline at Thirty Mile Point, on the south shore of Lake Ontario, has been called glacial in origin, and if that assumption is correct, it is glacial in age. If so, it was formed and overturned after deposition of the till which it incloses beneath the overturned crest.

Post-glacial.—The deformation of glaciated surfaces and of glacial deposits, and of uneroded tops of protruding folds and faults, is recognized as evidence of post-glacial origin. G. K. Gilbert was among the first to recognize the post-glacial age of folds near Caledonia and in Chautauqua and Jefferson counties, New York.[1] G. F. Mathews also recognized numerous post-glacial faults in the slates at St. John, New Brunswick.[2] The faults are very small, having a displacement of from less than an inch to 5 inches, but the glacial surfaces are distinctly deformed by these faults. Much more recently A. C. Lawson described numerous similar post-glacial faults of the same slight magnitude, 5 miles west of Banning, Ontario.[3] J. B. Woodworth has studied a series of small post-glacial faults in eastern New York, and has compared them with faults of like age in New England, Quebec, and New Brunswick.[4] Of the faults that occur in the five areas described in eastern New York, all are thrust faults in highly folded strata extending from Lower Cambrian to Lower Silurian. He has tabulated the movements in several of the series of small faults, and has taken the average displacement per yard for two adjacent areas, and gets as the result 1.9 inches in a yard, or 336.7 feet per mile.[5] No such minutely deformed glaciated surfaces were found in the area studied. Possibly this is because of the difference in the general attitude of the rocks. In the Lake Erie region they are in general flat-lying, while in eastern New York they are highly folded.

[1] G. K. Gilbert, *Amer. Geologist*, VIII (1891), 320–31; and *Proc. Amer. Assoc. Adv. Sci.*, XXXV (1887), 227.

[2] G. F. Mathews, *Amer. Jour. Sci.*, 3d Ser., XLVIII (1849), 501–3.

[3] A. C. Lawson, *Bull. Seis. Soc. Amer.*, I (1911), 159–66.

[4] J. B. Woodworth, *N.Y. State Mus. Bull. 107, Geol. 12* (1907), pp. 5–28.

[5] J. B. Woodworth, *ibid.*, p. 19.

Faults and folds with uneroded tops are in reality a phase of deformation of glaciated surfaces, because the loose, easily eroded tops rise above the general level of the glaciated surface and deform the basal part of the superjacent glacial deposits. The crest of a fold protruding up into the glacial till and including till beneath its overturned top, occurs along the southern shore of Lake Ontario, at Thirty Mile Point. Illustrations of this fold have been made by G. K. Gilbert,[1] and E. M. Kindle and F. B. Taylor.[2] This fold has a sharp crest of much shattered sandstones and shales extending up into the glacial clays in a way which indicates that the fold was formed after the drift had been deposited and the ice had receded. Similarly sharp crested small anticlines, though not overturned, have been illustrated by F. R. Van Horn.[3] These folds in the Chagrin shales have their sharp crests protruding into the superficial glacial till in a manner to mark them clearly as post-glacial. Had they been pre-glacial, the tops of soft, broken shale would have been eroded. A fold of this type with the top protruding into the drift above it occurs along the lake shore 3 miles east of Erie (Fig. 27).

By their relation to terraces and terrace deposits, the age of folds and faults can be determined still more definitely, so we can say they are not only post-glacial but post-terrace in age. Evidently if a fold or fault deforms the terrace, or if the loose shales at the top are uneroded in the terrace, they are younger than the terrace. E. M. Kindle and F. B. Taylor have recognized small folds in the Queenston shale south of Lake Ontario, that deform low terraces and so are known to be more recent than those terraces.[4] In the region south of Lake Erie, terraces are deformed by folds in this same manner. The anticline shown in Figure 38 deforms a 43-foot terrace. The gentle limb at the left is 200 feet wide and the steep one at the right 12 feet wide. Above the crest of the anticline a distinct ridge extends across the surface of the terrace in the direction of the axis. A view of this ridge above the fold is shown in Figure 37. Other folds, above which distinct low ridges occur in the terrace, in line with the axis of the fold, are shown in Figure 18, where the terrace is 14 feet high, and in Figure 26, where the terrace is about the same height.

[1] G. K. Gilbert, *Bull. Geol. Soc. Amer.*, X (1898), 133, Fig. 2.

[2] E. M. Kindle and F. B. Taylor, *Niagara Folio*, No. 190 (1913), Plate 19.

[3] F. R. Van Horn, *Bull. Geol. Soc. Amer.*, XXI (1909), 771–73, Figs. 1, 2, and Plate 54.

[4] E. M. Kindle and F. B. Taylor, *op. cit.*, p. 15.

A large number of folds were found with their uneroded crests extending up definitely into the terrace material above. Protrusion by a fold in which the topmost beds are resistant, might be expected,

FIG. 37.—A low ridge deforming the terrace above the fold in Figure 38

FIG. 38.—An unsymmetrical fold deforming a 43-foot terrace, the top of which is shown in Figure 37. Along Elk Creek 1 mile southeast of Girard, Pa.

if the folds are older than the terrace; but when the top of the fold consists of thin-bedded shales and sandstones, the uneroded crest gives evidence that the fold has been developed since the formation of the

terrace, or since the stream abandoned the old higher channel. Two illustrations of anticlines from which streams have eroded the crests

FIG. 39.—Anticline in the Trenton limestone related to the great thrust fault at Prospect, N.Y. Having eroded the crest from the fold, West Canada Creek has shifted its channel to the right.

FIG. 40.—A fold from which the crest has been eroded and flood-plain material deposited on the eroded top. Along the Ashtabula River, near Kingsville, Ohio.

are shown in Figures 39 and 40. The former is a fold in the Trenton limestone at the edge of the large fault at Prospect, New York. Here,

West Canada Creek, having eroded the crest of the fold, has cut its channel more deeply to the right, and has shifted in that direction.

FIG. 41.—Fold with crest uneroded in a 20-foot terrace. The book above the center of the picture covers the crest, and the terrace deposits extend down into the shale between the two books. Near North East, Pa.

FIG. 42.—Small anticline with crest uneroded in a low terrace. Open notebook behind the roots, and camera case near end of small thrust, mark top of shale. Seven miles southeast of Painesville, Ohio.

Another anticline with eroded crest is shown in Figure 40. Since the erosion of the crest the stream has shifted, and the materials of the

flood plain have been deposited on the truncated edges of the strata, indicating that the anticline is older than the flood plain.

While a large number of folds having their crests uneroded occur, it seemed difficult to get pictures clearly illustrating this condition. The loose shales at the top of the folds frequently are very like the fine material above, so the contrast is not sufficiently marked to show well in a picture. Figures 41 and 42 show two folds from which the loose shales at the crest have not been eroded, thus marking them younger than the terraces in which they occur. Figure 41 shows the detail of the crest represented in Figure 8. It occurs along Sixteen Mile Creek, one-half mile south of North East, Pennsylvania, in a terrace 20 feet high. The anticline has been overturned upstream, and the crest (covered by the upper book) has been forced up into the midst of the coarse terrace material. The lower edge of the book at the right rests on the topmost part of the shale to the right of the anticline. The crest of this fold, overturned upstream, clearly is post-terrace. Figure 42 shows another small anticline, from the crest of which the loose shale has not been eroded. The open notebook (back of the roots to the left of the crest), marks the juncture of shale with flood-plain material, while the camera case marks it down on the right limb of the fold. A small fault with a horizontal displacement of 2 feet and 3 inches occurs at the right. Figures 18, 26, and 38 also represent folds in terraces with their crests uneroded. As indicated above, the age of these folds is fixed clearly as younger than the terraces in which they occur, in each case where the non-resistant crest is uneroded.

In the same manner that the uneroded top of a fold indicates that it is more recent than the terrace on which it occurs, so the uneroded top of a fault indicates its recency. Two faults illustrating the difference between a pre-terrace fault and a post-terrace one are shown in Figures 43 and 44. Both are in the upper part of the Chagrin shales along Euclid Creek, about 9 miles east of Cleveland. Both are overthrust upstream in a general southeasterly direction. The one in Figure 43 is in a terrace 10 feet high, $2\frac{1}{2}$ miles south of Euclid, and the other is three-fourths of a mile farther upstream, in a terrace 8 feet high. In Figure 43 the thin sandstone bed above (a) on the downthrow side of the plane is the same as the one above (a'') on the upthrow side. The overthrust of the bed from the right of (a) would carry it to some such point as (a'), but the vertical extension of the overthrust has been eroded to the gradient plane of the former stream channel upon which the upper material of the terrace has been deposited. Thus the eroded

top indicates clearly that the displacement occurred before the formation of the terrace. In contrast with this condition, the fault shown in Figure 44 has the upthrow side still uneroded in a terrace 8 feet in height.

FIG. 43.—A small fault with eroded top in the Chagrin shales near Euclid, Ohio. The same bed occurs above (*a*) and (*a''*).

FIG. 44.—Overthrust fault with top uneroded, south of Euclid, Ohio

The fault plane dips at a very low angle in this upper part. At the left, to the northwest, it dips more abruptly beneath the floor of the valley. The horizontal displacement is 5 feet, extending from (*a*) to

the camera case above at the right. The end of the upthrown side abuts against the flood-plain material at the right, and the soft shales have not been eroded from the top. This uneroded top proves that the displacement is younger than the terrace.

NATURE AND ORIGIN OF STRESSES IN ROCKS IN AREA

Where and how have the stresses originated that formed the folds and faults? Are they merely local, or are they general for the region? Are they cumulative, or residual? As the magnitude of the deformations may have direct bearing upon these questions, that will be noted first. A few of the folds have a width of from 300 to 500 feet, but most of them are less than 100 feet. In regard to the thickness of the strata involved, some folds deform terraces 40 to 60 feet high, and extend an unknown distance below the bottom of the valleys. The size of the folds would seem to indicate that any single fold does not reach a very great depth. In some instances faults below grade into folds above, and these faults may reach down for a considerable distance. In the case of one fold along Elk Creek, south of Girard, Pennsylvania (Fig. 38), there is a constant escape of gas from the crest where the stream crosses it. The gas horizons of this region lie chiefly between 500 and 700 feet in depth. This seems to indicate that not alone the most superficial strata are affected by the deformation. A number of folds of the same magnitude occur in the area.

Cumulative stresses.—That the earth's crust has a very considerable rigidity which must be overcome before deformation can take place is a fact now generally recognized. That the great movements of the earth's crust are periodic has been emphasized by many eminent geologists.[1] This periodicity has been proved by the earth's history. R. T. Chamberlin recently has summarized the diastrophic periods of the Paleozoic, noting their relative importance and value as criteria for separating the rock systems.[2] Between the periods of great deformation, inter-periods of relative quiescence have occurred, during which land masses remained in a stable condition, while erosion has proceeded sufficiently long to reduce areas to the base-leveled condition of a peneplain. Because of the rigidity of the earth, and of this periodicity of the great diastrophic movements, it is conceivable that there are long periods of stress accumu-

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, I (1905), 588–89, and III, 192–93; T. C. Chamberlin, *Jour. Geol.*, XVII (1909), 689; C. Schuchert, *Bull. Geol. Soc. Amer.*, XX (1908), 500; Bailey Willis, *Science*, XXXI (1910), 246–48.

[2] R. T. Chamberlin, *Jour. Geol.*, XXII (1914), 315–45.

lation, in which the stresses become more and more acute until they are sufficiently strong to overcome the strength of the earth's crust and its rigid interior. When this mastering degree of intensity has been reached, readjustment by movement takes place in the various types of deformation. These adjustments continue until all the stresses are more or less perfectly compensated. After each great deformative period there follows a period of quietude in which the accumulation of stresses again begins to develop toward a higher and higher intensity.

If there are these long intervals of stress accumulation preceding each diastrophic movement, it is possible that although incompetent to deform the great masses of the earth's exterior, they still may have sufficient force to overcome locally some of the weaker parts, particularly if in addition to the more general stresses the rocks of an area are subjected to additional local ones. That these cumulative stresses are likely to be widespread may be deduced from the large areas affected by compensating adjustments.

It is conceived then that during a period of relative quietude for this area, stresses have accumulated which, possibly by the addition of local stresses, to be noted later, have reached an intensity sufficient to deform the rocks on a small scale. If the great periodic or inter-periodic stresses have been accumulating in this area, and have contributed, in part at least, to the deformation of the rocks, the small folds and thrust faults indicate that they are largely lateral, or tangential.

Residual stresses.—In connection with the climactic accumulation of stresses with the consequent strains and deformative movements, it was noted that the compensation of the force developed might be more or less complete. If the compensation were absolutely complete, the new era following the deformative one would start out with a clean record. Thus one series in a cycle would be: stresses developed slowly to great intensity, great diastrophic movements, stresses all relieved, and rocks perfectly at ease until the beginning of a new series of cumulative stresses is initiated. Another conception may be that compensation is not complete; that after all the force of the great stresses competent to cause deformation has been relieved, there still remain residual stresses, which, though real in character, are incompetent to carry the deformation farther. Thus the new era succeeding the deformation period would have bequeathed to it some of the stresses which may have been initiated early in the preceding period of general quietude.

Still another conception may be that compensation is variable throughout any large area affected by deformative forces, not alone

because of the variable rigidity and elasticity of the rocks, but more largely in the localization of the forces engendered by the stresses, and the alignment of those forces in one general direction. Illustrations of this localization and alignment are seen in the closely folding, overturning, and thrust faulting of the central and southern parts of the Appalachians. If it be true that a great thrust of part of the earth's exterior, and possibly a part of the interior, was directed against the southeastern margin of the Appalachian region, it is possible that compensation was most perfect along this margin, where the force was applied and where the close folds were overturned, broken, and overthrust one far upon another. Toward the northwest, compensation may have been less complete as the folds became more open. Still farther to the northwest, beyond where the gentle, open folds were formed, lateral stresses may have developed which, though considerable in intensity, were incompetent to deform the rocks. It is the conception, then, for the area studied, that tangential stresses very considerable in amount were initiated here at the time when the marked diastrophic movements formed the great Appalachian structural unit, and that these stresses have remained as a residuum since that time. It is thought that to these residual stresses later stresses were added, making their combined force sufficient to fold and rupture the rocks. J. Barrell, in his recent studies, has expressed the idea that strains within the earth's crust may be borne for very long periods of time.[1]

RELATION TO LARGER MOVEMENTS

Having noted that very considerable residual stresses probably have existed for an extremely long time, it is the purpose now to link the minor movements of this area with much larger ones; the uptilting of the northern part of the Great Lakes area and the region to the northeast, and the uplift and deformation of the Harrisburg peneplain in northern Pennsylvania, northeastern Ohio, and southern New York.

Northeastward tilting.—It has long been recognized that the region of the Great Lakes and the area to the northeast of these lakes have been undergoing a tilting movement during and since the Pleistocene. In this movement the rise has increased in magnitude from the Great Lakes region toward the northeast. From a large number of measurements of changes in the levels of the lakes on the north and south sides,

[1] J. Barrell, *Jour. Geol.*, XXII (1914), 310.

[2] G. K. Gilbert, *Eighteenth Ann. Rept. U.S.G.S.*, XVIII (2) (1896–97), 636.

G. K. Gilbert[1] has deduced the result of a tilting .42 of a foot for 100 miles in one hundred years. The tilting during and since the Pleistocene also has been measured and computed, by determining the amount of warping of the old water lines marked by beach ridges and cut bluffs which are now far above the present level of the lakes. A large number have worked on the problems of the uplift and tilting of this lake area, and H. L. Fairchild in a recent article has given the bibliography of this work.[2] The direction of the isobases for New York and northern Pennsylvania, given by Fairchild "with an inclination from the latitude parallels of 20°, 70° divergence from the meridians,"[3] corresponds closely with the extensions of those given by J. W. Goldthwait for the Lake Michigan-Huron region;[4] also with those given earlier by G. K. Gilbert for the entire Great Lakes region.[5] Just where the hinge for this uplift should be placed with reference to Lake Erie is not definitely settled. Goldthwait apparently would place it at the extreme eastern end of the lake,[6] while Fairchild would place it west of the center.

If then, the hinge line of this uplift passes through, or along, the edge of the area studied, this area is in a critical position with reference to the uplift. The position is critical because of tangential stresses which may have been related to the tilting in a zone parallel to the hinge. That the tilting and tangential movements have been synchronous is suggestive. The tilting begun during the Pleistocene continues to the present. Numerous folds and faults are post-glacial, some giving evidence of reaching almost to the present time.

If tangential stresses are related to this uplift, folds resulting from them should have their axes trending in a general way parallel with the hinge line and the isobases. As noted above, the isobases trend about 80° west of north, when extended as straight lines from the Lake Michigan-Huron region, but if the isobases curve southward across Lake Erie, the direction would be north 60° or 70° west.

Table V gives the direction of the axes for folds in the Lake Erie region, of which illustrations are shown, and is quite representative. While a very few have axes either about east and west or north and south, two-thirds have a northwest trend, the majority lying between N.40°W.

[1] G. K. Gilbert, *Eighteenth Ann. Rept. U.S.G.S.*, XVIII (2) (1896-97), 636.

[2] H. L. Fairchild, *Bull. Geol. Soc. Amer.*, XXVII (1916), 255-62.

[3] H. L. Fairchild, *ibid.*, 238, Plates 10 and 12.

[4] J. W. Goldthwait, *Canada Dept. Min. Geol. Surv. Mem. 10* (1910), Fig. 3, opp. p. 40.

[5] G. K. Gilbert, *op. cit.*, p. 640, Fig. 100.

[6] J. W. Goldthwait, *Bull. Geol. Soc. Amer.*, XXI (1910), Plate 5, opp. p. 233.

and N.80°W., and about one-third have a northeast trend. The trend of the folds may seem too variable to align them into one or even two series, but minor folds of any series are not necessarily closely parallel with one another. For comparison, the trend of a number of folds on the northwest border of the Appalachians was determined from the geological folios and arranged in Table VI. This table shows a large variation in the trend of the axes of the smaller folds of a series adjacent to the larger Appalachian structures. A comparison of Tables V and

TABLE V

SHOWING DIRECTION OF AXES OF FOLDS IN THE LAKE ERIE REGION

Northwest Trend				Northeast Trend	
Fig. 2.	N.10°W.	Fig. 14.	N.50°W.	Fig. 11.	N.10°E.
Fig. 27.	N.20°W.	Fig. 31.	N.60°W.	Fig. 26.	N.25°E.
Fig. 28.	N.30°W.	Fig. 33.	N.60°W.	Fig. 8.	N.35°E.
Fig. 12.	N.35°W.	Fig. 25.	N.80°W.	Fig. 41.	N.35°E.
Fig. 40.	N.40°W.	Fig. 34.	N.80°W.	Fig. 24.	N.50°E.
Fig. 4.	N.45°W.	Fig. 42.	N.80°W.		

East-West and North-South Trend	
Fig. 23.	E.-W.
Fig. 38.	N.-S.

TABLE VI

SHOWING TREND OF AXES OF FOLDS ALONG THE NORTHWESTERN EDGE OF THE APPALACHIANS IN PENNSYLVANIA

N.15°E.	N.35°E.	N.80°E.
N.15°E.	N.40°E.	N.80°E.
N.28°E.	N.45°E.	
N.30°E.	N.60°E.	N.42°W.
N.35°E.	N.70°E.	N.80°W.

VI shows about the same degree of variation in both, even though the directions in the latter represent the axes of folds along the border of the Appalachians.

Doming of peneplain.—M. R. Campbell[1] has adduced evidence on a physiographic basis to show that the Harrisburg peneplain has been deformed by an irregular domelike uplift, with the maximum of elevation in McKean and Potter counties, Pennsylvania, and in southern New York. This peneplain rises from 500 feet near Harrisburg, to 2,200 feet in the northern part of the state. The area along the southern border of Lake Erie forms the northwestern part of this domelike uplift,

[1] M. R. Campbell, *Bull. Geol. Soc. Amer.*, XIV (1902), 277–96.

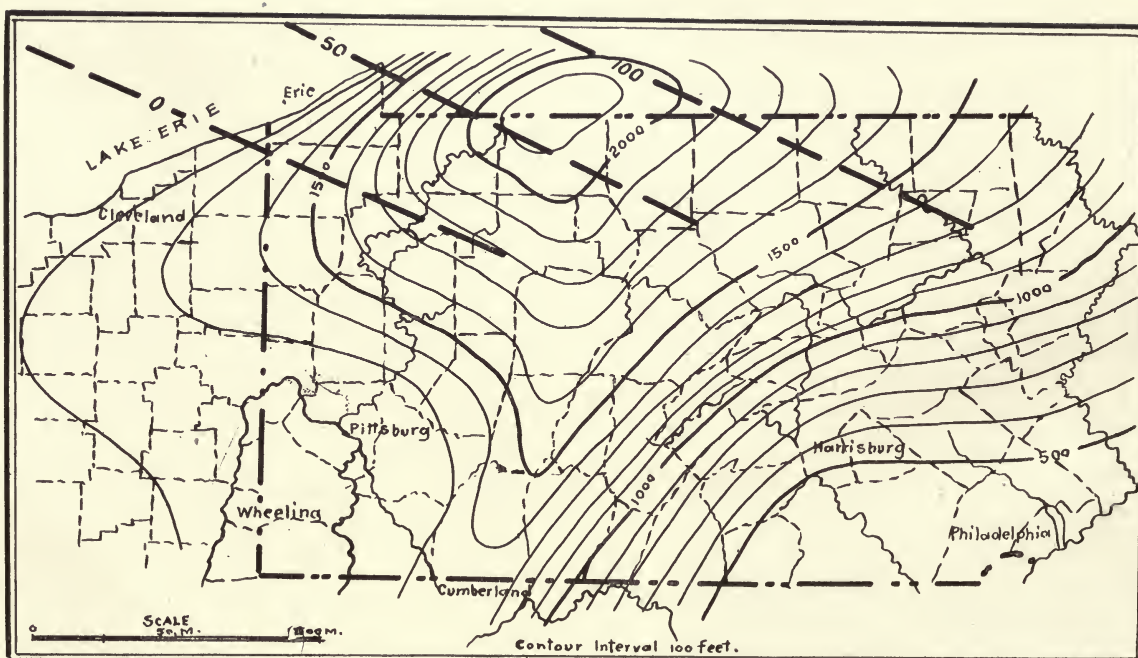


PLATE III

Map Showing Isobases of Deformed Harrisburg Peneplain with the Isobases of the Uplift toward the Northeast Dotted across the Former (modified from Campbell and Fairchild).

and in this part of the dome isobases trend north 60° to 70° east. While the axes of the majority of folds trend northwest, a second series have axes trending in a northeasterly direction, and these are closely parallel with the direction of the isobases on the northwest side of the dome. It is worthy of note that the trace of the faults in the Syracuse region is nearly east and west, as they lie on the north side of the dome, and parallel the general trend of the isobases there. Thus, of the two series of folds, one series with northwest trend parallels the isobases of tilting to the northeast, while the other parallels the isobases of the domed peneplain. (See Plate III.)

This peneplain is of early Tertiary age, so its deformation has been since that time. How recent elevation has been is not known. It is quite possible it may have been very recent, or it may have continued to the present. If elevation in the doming has been recent, we have elevation of two types at the same time in adjacent regions.

While in the elevation of these two areas, the vertical component in the stresses was doubtless dominant, it is thought there would be a horizontal component also, which would increase in intensity toward the margin of the dome and toward the hinge of the tilted area. Were the uplifts synchronous, lateral stresses from the south and southeast would meet those from the northeast at an angle, and the two sets be combined. If uplifts alternated in time, stresses first from one direction and then from the other would be dominant. The area studied is then in a most critical position, being in the border zone of these two large movements, caught as a wedge between the two uplifts. It is at least very significant that in the open part at the western end of the area where the isobases diverge, the folds are scattered, and the tangential movement is comparatively slight, while in southern New York, on the north side of the dome, where the isobases converge and the uplifts come together and possibly overlap, the folds are larger, and overthrusts of greater magnitude occur. Thus it is thought that in connection with these two great movements of tilting and doming, lateral stresses have been initiated in this border area, competent to cause the minor tangential movements.

SUMMARY

The following conclusions have been reached with reference to these minor deformations in the area bordering on and adjacent to the southern edge of Lake Erie. The deformation consists of folds and thrust faults, indicating the predominance of lateral stresses; the minor folds present most of the types common in major ones, though typical closed

and recumbent folds are absent; of the many explanations considered for the origin of the folds and faults, most of them have been rejected as wholly inapplicable or markedly incompetent quantitatively for this area; while ice expansion and weathering may have caused some very small superficial flexures, and a few very small folds in weak or disturbed strata may be due to glaciation and landslides, it is thought that most of the folds and faults are the result of widespread lateral compressive stresses; a few of the folds are pre-Pleistocene, possibly Permian or later, a few very small ones are Pleistocene, but most of them are post-glacial, and a number are post-terrace; cumulative stresses developing between the great diastrophic periods are thought to have affected the rocks of this area, and possibly, also, some strains residual from one or more of the great deformative periods have been bequeathed to the rocks here, and these strains were linked with later ones initiated by recent movements; and finally, the minor movements of the area are thought to be genetically related to the two larger ones—tilting of the Great Lakes region to the northeast, and doming of the *Harrisburg Peneplain* to the southeast.

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